WATER FOOTPRINT AND VIRTUAL WATER FLOW OF TRADE CASSAVA STARCH AND REFINED SUGAR OF THAILAND

Manuswee Phanichnok

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วอเตอร์ฟุตพริ้นท์และการไหลของน้ำเสมือนกับการค้าของแป้งมันสำปะหลังและน้ำตาลทรายขาวบริสุทธิ์ของประเทศไทย

นางสาวมนัสวี พานิชนอก

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
สาขาวิชาชีววิทยาสิ่งแวดล้อม
มหาวิทยาลัยเทคโนโลยีสุรนารี
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WATER FOOTPRINT AND VIRTUAL WATER FLOW OF TRADE CASSAVA STARCH AND REFINED SUGAR OF THAILAND

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Thesis Examining Committee

N. Muangsan
(Assoc. Prof. Dr. Nooduan Muangsan)
Chairperson

P. Suwan
(Asst. Prof. Dr. Pongthep Suwanwaree)
Member (Thesis Advisor)

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มนัสวี พานิชนอก : วอเตอร์ฟุตพริ้นท์และการไหลของน้ำเสมือนกับการค้าของแป้งมันสำปะหลังและน้ำตาลทรายขาวบริสุทธิ์ของประเทศไทย (WATER FOOTPRINT AND VIRTUAL WATER FLOW OF TRADE CASSAVA STARCH AND REFINED SUGAR OF THAILAND). อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.พงศ์เทพ สุวรรณวารี, 224 หน้า.

การผลิตแป้งมันสำปะหลังและน้ำตาลถือเป็นอุตสาหกรรมเกษตรที่สำคัญของประเทศไทย การปลูกมันสำปะหลังและอ้อย รวมถึงโรงงานแปรรูปแป้งมันสำปะหลังและน้ำตาลกระจายอยู่ทุกพื้นที่ของประเทศไทย ซึ่งทำให้เกิดผลกระทบต่อทรัพยากรน้ำ ทั้งการขาดแคลนน้ำและคุณภาพ วอเตอร์ฟุตพริ้นท์เป็นเครื่องมือวัดปริมาณน้ำใช้ทั้งหมดเพื่อการบริโภคในระดับบุคคลหรือประเทศ เป็นการทำแผนที่ภาพรวมที่ชัดเจนของการใช้น้ำเพื่อการผลิตสินค้า โดยน้ำใช้ที่เกิดจากจุดที่ผลิตได้ไหลออกจากพื้นที่ผลิตไปยังพื้นที่อื่น ๆ ที่เกี่ยวข้องกับการบริโภคหรือการค้า วัตถุประสงค์ของการวิจัยนี้คือ การคำนวณปริมาณการใช้น้ำโดยเฉลี่ยของการผลิตแป้งมันสำปะหลังและน้ำตาลทรายขาวบริสุทธิ์ นับตั้งแต่การใช้น้ำเพื่อการเพาะปลูกพืชและขั้นตอนการแปรรูปเป็นผลิตภัณฑ์ รวมถึงปริมาณการไหลของน้ำเสมือนที่สัมพันธ์กับการค้าสินค้าดังกล่าวระหว่างประเทศไทยกับต่างประเทศ ในช่วงปี พ.ศ. 2551-2556

ผลการศึกษาพบว่า การปลูกมันสำปะหลังมีความต้องการน้ำเฉลี่ยทั้งประเทศภายใต้เงื่อนไขความต้องการน้ำของพืชเท่ากับ 9,074 ลบ.ม./เฮกตาร์ ส่วนความต้องการน้ำภายใต้เงื่อนไขการให้น้ำทางชลประทานเท่ากับ 9,051 ลบ.ม./เฮกตาร์ นอกจากนี้ ค่าวอเตอร์ฟุตพริ้นท์ทั้งหมดเฉลี่ยทั้งประเทศภายใต้เงื่อนไขการให้น้ำทางชลประทานมีค่าเท่ากับ 528 ลบ.ม./ตัน แบ่งออกเป็นประเภทกรีนเท่ากับ 187 ลบ.ม./ตัน ประเภทบลูเท่ากับ 251 ลบ.ม./ตัน และประเภทเกรย์เท่ากับ 90 ลบ.ม./ตัน สำหรับการปลูกอ้อยพบว่ามีความต้องการน้ำเฉลี่ยทั้งประเทศภายใต้เงื่อนไขความต้องการน้ำของพืชเท่ากับ 11,798 ลบ.ม./เฮกตาร์ ส่วนความต้องการน้ำภายใต้เงื่อนไขการให้น้ำทางชลประทานเท่ากับ 11,766 ลบ.ม./เฮกตาร์ ค่าวอเตอร์ฟุตพริ้นท์เฉลี่ยทั้งประเทศภายใต้เงื่อนไขการให้น้ำทางชลประทานเท่ากับ 195 ลบ.ม./ตัน แบ่งออกเป็นประเภทกรีนเท่ากับ 103 ลบ.ม./ตัน ประเภทบลูเท่ากับ 58 ลบ.ม./ตัน และประเภทเกรย์เท่ากับ 34 ลบ.ม./ตัน

วอเตอร์ฟุตพริ้นท์ทั้งหมดที่ใช้ผลิตแป้งมันสำปะหลังพบว่ามีค่าเท่ากับ 1,962 ลบ.ม./ตัน แบ่งออกเป็นประเภทกรีนเท่ากับ 684 ลบ.ม./ตัน ประเภทบลูเท่ากับ 933 ลบ.ม./ตัน และประเภทเกรย์เท่ากับ 345 ลบ.ม./ตัน สำหรับปริมาณน้ำเสมือนทั้งหมดที่ใช้ผลิตน้ำตาลทรายขาวบริสุทธิ์มีค่าเท่ากับ 5,276

ลบ.ม./ตัน แบ่งออกเป็นประเภทกรีนเท่ากับ 2,783 ลบ.ม./ตัน ประเภทบลูเท่ากับ 1,571 ลบ.ม./ตัน และประเภทเกรย์เท่ากับ 922 ลบ.ม./ตัน ปริมาณการใช้น้ำในภาคอุตสาหกรรมจะมีความแตกต่างกันออกไปขึ้นอยู่กับนโยบายการนำน้ำกลับมาใช้ใหม่ การควบคุมการผลิตที่ดีและเทคโนโลยีการผลิต

สำหรับการไหลของน้ำเสมือนกับการค้าแป้งมันสำปะหลังของประเทศไทย พบว่ามีการไหลออกนอกประเทศสุทธิเท่ากับ 3.70 พันล้าน ลบ.ม./ปี โดยการไหลของน้ำเสมือนไปยังประเทศจีนมากที่สุด รองลงมาคือ อินโดนีเซีย ไต้หวัน มาเลเซีย และญี่ปุ่น ส่วนการไหลของน้ำเสมือนสุทธิกับการค้าน้ำตาลทรายขาวบริสุทธิ์ของประเทศไทยเท่ากับ 13.88 พันล้าน ลบ.ม./ปี โดยการไหลของน้ำเสมือนไปยังประเทศกัมพูชามากที่สุด รองลงมาคือ อินโดนีเซีย อิรัก เวียตนาม และอินเดีย พบว่า มากกว่าร้อยละ 80 ของน้ำเสมือนสุทธิทั้งสองผลิตภัณฑ์ไหลออกไปยังประเทศต่าง ๆ ในทวีปเอเชีย ประเทศไทยซึ่งเป็นผู้ผลิตและส่งออกแป้งมันสำปะหลังและน้ำตาลทรายขาวบริสุทธิ์รายใหญ่ของโลก จำเป็นที่จะต้องกำหนดปริมาณการผลิตและการส่งออกที่เหมาะสม และมีการบริหารจัดการทรัพยากรน้ำที่ถูกต้องเพื่อป้องกันภาวะการขาดแคลนน้ำในอนาคต

สาขาวิชาชีววิทยา ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา 2559 ลายมือชื่ออาจารย์ที่ปรึกษา ____________________

MANUSWEE PHANICHNOK : WATER FOOTPRINT AND VIRTUAL
WATER FLOW OF TRADE CASSAVA STARCH AND REFINED SUGAR
OF THAILAND. THESIS ADVISOR : ASST. PROF. PONGTHEP
SUWANWAREE, Ph.D. 224 PP.

CASSAVA/SUGARCANE/WATER FOOTPRINT/CROP CULTIVATION/PROCESSING/TRADE/THAILAND

Cassava starch and sugar are important parts of the agro-industry of Thailand. Cassava and sugarcane are extensively cultivated and processed all over of Thailand and they have a large impact on water resources and create stress on water availability and quality. The water footprint (WF) is a tool for measuring the water consumed by an individual or a country. WF assists to provide a clear overview of the mapping of water used by points that flow out, related to their product consumed and trade. The objectives of this study were to calculate the WF of cassava starch and refined sugar, including virtual water flow (VWF) of their trade in Thailand during the period 2008-2013.

The study indicated that the average crop water use evaporation (CWU_{eva}) of cassava cultivation estimated under the crop water requirement (CWR) option was equal to 9,074 m^3/ha, while that estimated under the irrigation schedule-option was equal to 9,051 m^3/ha. The average total water footprint (WF_{total}) estimated under irrigation schedule-option was equal to 528 m^3/ton, classified into green, blue and grey of 187, 251 and 90 m^3/ton, respectively. The average CWU_{eva} of sugarcane cultivation estimated under the CWR-option was equal to 11,798 m^3/ha, while that estimated under the irrigation schedule-option was equal to 11,766 m^3/ha. Moreover, the average WF_{total}

estimated under the irrigation schedule-option was equal to 195 m^3/ton, classified into green, blue and grey of 103, 58 and 34 m^3/ton, respectively.

The WF_{total} of cassava starch was 1,962 m^3/ton, in which the value of green, blue and grey was 684, 933 and 345 m^3/ton, respectively. In the case of refined sugar, the WF_{total} was 5,276 m^3/ton, classified into green, blue and grey as 2,783, 1,571 and 922 m^3/ton, respectively. The difference in volume of water use in the industrial sector depends on the policy of water saving, processing control and technology.

For the net virtual water flow (VWF_{net}) of trade cassava starch of Thailand, an average of 3.70 Gm^3/year export was observed. China was the largest country to import, followed by Indonesia, Taiwan, Malaysia and Japan. Similarly, the VWF_{net} of refined sugar exports of Thailand was 13.88 Gm^3/year. Cambodia consumed the most refined sugar, followed by Indonesia, Iraq, Vietnam and India. The results showed that Thailand exported more than 80% VWF_{net} of both products to countries in Asia. Thailand is one of the biggest producers and exporters of cassava starch and refined sugar in the world. The Thai government should determine the appropriate amount of production and their export quantity and good management practices to prevent water shortages in the future.

School of Biology Student's Signature ______________

Academic Year 2016 Advisor's Signature ______________

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Manuswee Phanichnok

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LIST OF ABBREVIATIONS

α = chemical leaching-runoff fraction

ASEAN = Association of Southeast Asian Nations

Avg = average

°C = Degree of Celsius

cal = calories

cm = centimeter

CWR = Crop Water Requirement

CWU = Crop Water Use

e. g. = for example

ET = crop evapotranspiration

et al. = et alia (and others)

ET_a or $ET_{a\ adj}$ = crop evapotranspiration under non-standard conditions

ET_c = crop evapotranspiration under standard conditions

ET_o = reference crop evapotranspiration

EU = European Union

FAO = Food and Agriculture Organization of the United Nations

f_p = product fraction

f_v = value fraction

G = giga

ha = hectare

IR = Irrigation Requirement

LIST OF ABBREVIATIONS (Continued)

J = joule

k = kilo

K = potassium

K_c = crop coefficient

kg = kilogram

K_s = crop coefficient that describes the effect of water stress on crop transpiration

L = liter

Lao PDR = Lao People’s Democratic Republic

LCA = Life Cycle Assessment

LCI = Life Cycle Inventory

lgp = length of growing period

M = mega

m = meter

mm = millimeter

N = nitrogen

Nm = newton meter

Opt = option

P = phosphorus

Pa = pascal

P_{eff} = effective rainfall

pH = potential Hydrogen

LIST OF ABBREVIATIONS (Continued)

% = percentage

s = second

SCS = Soil Conservation Service

UAE = United Arab Emirates

UK = United Kingdom

USA = United States of America

USDA = United States Department of Agriculture

VWC = Virtual Water Content

VWF = Virtual Water Flow

WF = Water Footprint

CHAPTER I

INTRODUCTION

1.1 Statement of the problem

Many countries around the world are suffering from food scarcity. The major contributing factors to this problem are natural disasters, land degradation, war, power shortages and water scarcity. Water scarcity represents a critical constraint on food production as it is one of the pivotal sources which supports food production and food scarcity. Demands for water from industrial agriculture, expanding urban areas and increasing population have created severe pressure on water supplies. Agricultural sector withdrawals are one of the most water sensitive areas that is responsible for 70% of the world's freshwater. Cassava is one of the important foods and agricultural commodities of the world, especially in Asia and Africa. Cassava production was around 1.8% of the world's gross crop production value in 2016 (FAOSTAT, 2016). Apart from foods, cassava is very versatile and its derivatives and starch are applicable in many types of products such as foods, confectionery, sweeteners, glues, plywood, textiles, paper, biodegradable products, monosodium glutamate, and drugs. Moreover, cassava chips and pellets are used in animal feed and alcohol production (IITA, 2014). World trade in cassava is estimated at around 70% in the form of dry cassava, which contributes to animal feed and the remainder is used mostly in the form of starch for food processing and industrial purposes. According to FAOSTAT (2014), global cassava cultivation was about 20.7 million hectares and production has since increased by up to 270 million tons per year. Thailand is the third largest cassava producer in the world and is the largest exporter of cassava starch. The production of cassava in Thailand is in high demand particularly in Asia, USA, Australia, Africa and Europe.

On the other hand, sugarcane is the main producer of sugar and sweeteners, and is an economically important crop that is the mainstay of many developing countries principally in Latin America, the Caribbean, but also in southern Africa, Asia and the Pacific (Mulherin, 1988). Sugarcane is the world's largest crop and its cultivation is estimated at about 26.5 million hectares which yields a harvest of about 1.87 billion tons per year. Brazil is the largest sugarcane producer of the world, while Thailand is one of the world's leading sugarcane producers and sugar exporters.

Thailand is an agricultural country that produces agricultural products both for national consumption and for export worldwide. Freshwater is required for agriculture and power-generating practices at a maximum of 75.5%, followed by ecological maintenance (17.6%), domestic consumption (3.5%), and industry and tourism (3.4%) (Udomratanasilpa, 2008). Most of the irrigated areas in Thailand are in the Central Plain (45%), followed by the North (26%), the Northeast (17%), and the South (12%) regions (Doppler *et al.*, 2009). Cassava and sugarcane are significant food plants for the production of cassava starch and sugar which are cultivated in Northern, Northeastern and the Central Plain of Thailand. The average yearly harvested area of cassava in Thailand for 2008-2013, as reported by the OAE (2010 and 2013a) was around 1.26 million hectares, which resulted in the production of 25.9 million tons, while the harvested area of sugarcane was 1.14 million hectares, which resulted in the production of 83.8 million tons. At present, cassava and sugarcane are extensively cultivated over the country which has very large evaporation of infiltration rainwater and irrigation for their crop areas. The leaching of nutrients from agricultural fields is one of the main causes of non-point source pollution of surface and subsurface water bodies (Mekonnen and Hoekstra, 2010). Fertilizers and chemicals applied on the fields are important to illustrate the amount of the N-fertilizer that leaches through the surface and groundwater. Moreover, in industrial processing high water consumption and wastewater generation is also an important sector. Thus, freshwater use is required for cassava starch and refined sugar production and requires to assimilate water pollution to get higher water quality standards that shows how much water is withdrawn from natural water resources to produce their products.

The water footprint (WF) concept was introduced by Hoekstra and Hung (2002), as an indicator of how to calculate the total volume of freshwater that is used to produce the products and services along the different steps of the supply chain. Chapagain and Hoekstra (2004) described the WF as an indicator of human appropriation of freshwater resources that incorporates both direct and indirect water use of consumers or producers. Moreover, the water consumed in the production process of an agricultural or industrial product has been called the ‘virtual water’ contained in the product (Allan, 1998). If one country exports a water intensive product to another country, it is exported in virtual form (WWC, 1998), this represents the water use flow to support the water-scarce countries. WF shows water consumption volumes by source and the amount of water that is polluted by types of pollution. The WF consists of three components: the blue, green and grey WFs. The blue WF refers to volume of surface and groundwater in a catchment area that is evaporated due to crop growth. The green WF expresses the volume of rainwater that evaporates during the crop growth and the grey WF defines the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards (Hoekstra *et al.*, 2011). This tool has evolved independently from Life Cycle Assessment (LCA) that focuses on the water-resource management perspective. The aim of this study was to calculate the WF and virtual water flow (VWF) of trade of cassava starch and refined sugar of Thailand. This calculation distinguishes three components: green, blue and grey WFs. The information from WF and VWF will be useful for water resources planning and policy management, which distributes water use during crop production, including industrial processing and worldwide trade.

1.2 Research objectives

The principal objectives of this study are:

1. To assess the water footprint and the virtual water flow of trade cassava starch of Thailand for the period of 2008-2013.
2. To assess the water footprint and the virtual water flow of trade refined sugar of Thailand for the period of 2008-2013.

1.3 Scope and limitations of the study

1. In this study, the green, blue and grey WFs and VWF of trade cassava starch and refined sugar of Thailand were assessed during 2008-2013.
2. The calculation methodology of WF followed The Water Footprint Assessment Manual, written by Hoekstra *et al.* (2011).
3. The study areas of crop cultivation for this study covered three regions: Northern, Northeastern and the Central Plain of Thailand.

4. Cassava and sugarcane planting dates are the same determined on 1st May. The harvest date of cassava is on 25th April and the crop cycle is 360 days. In addition, the harvest date of sugarcane is on 16th March and the crop cycle is 320 days.

5. Three cassava starch factories and one refined sugar factory which are located in Nakhon Ratchasima province were selected as case studies for this study.

6. The WF of cassava starch and refined sugar of Thailand was calculated based on the average amount of water use in industrial processing for this case study and the data for the amount of water use was obtained from the life cycle inventory (LCI) analysis of cassava starch and refined sugar processing from previous studies in Thailand.

CHAPTER II

LITERATURE REVIEW

This chapter provides a review of the literature respecting the world's and Thailand's freshwater resources and the theory explaining howation the WF concept has been developed to assess water needs for the production of the goods and services that are useful in water management and, finally, an overview data of cassava and sugar production and their trade in Thailand is given.

2.1 Freshwater resources and availability

2.1.1 Global fresh water resources

Freshwater resources are important and are under stress around the world. Surface water and underground aquifers generally supply freshwater for irrigation, drinking, and sanitation. Increasing global water demand is influenced by population growth, while the global gross domestic product (GDP) rose at an average of 3.5% per year from 1960 to 2012 and much of this economic growth has come at a significant social and environmental cost. Water withdrawals for agriculture and energy can further exacerbate water scarcity. Freshwater withdrawals for energy production currently account for 15% of the world's total water (WWAP, 2014) and are expected to increase by 20% by 2035 (IEA, 2012). The agricultural sector is already the largest user of water resources, accounting for roughly 70% of all freshwater withdrawals globally, and over 90% in most of the world's least-developed countries (WWAP, 2014). Practices like efficient irrigation techniques can have a dramatic impact on reducing water demand, especially in rural areas. For distribution and availability of freshwater resources, although precipitation and runoff water can be erratic, different areas of the globe receive different quantities of water over any given year. There can be considerable variability between arid and humid climates and over wet and dry seasons (UNESCO, 2015).

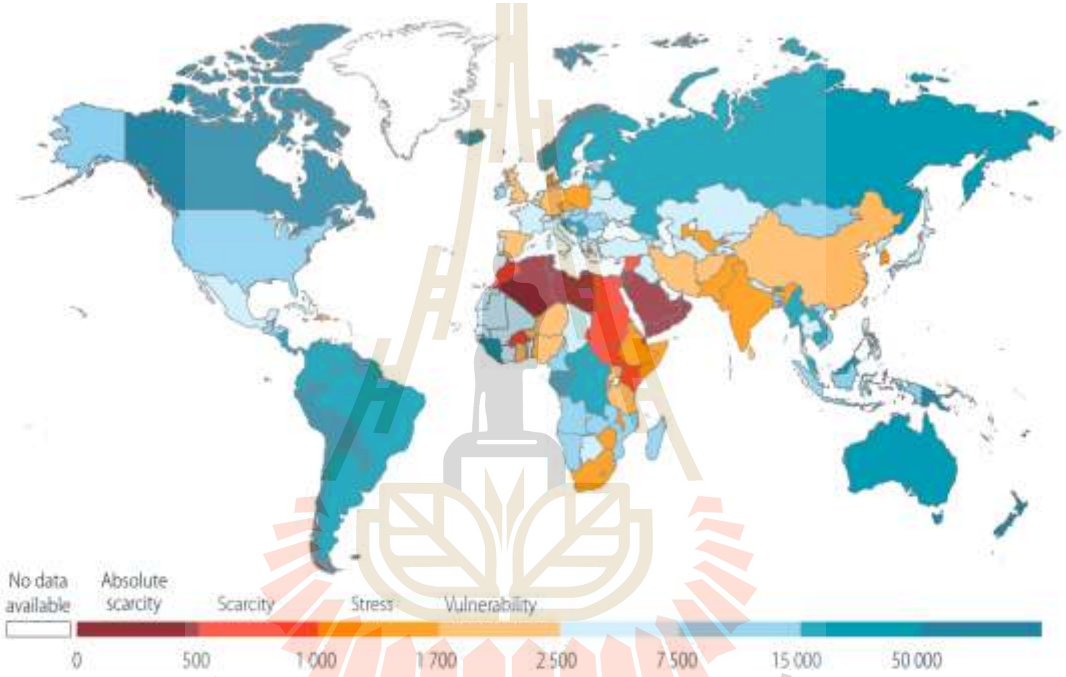


Figure 2.1 Total renewable water resources per capita (m^3) 2013.

Source: WWAP, prepared with data from FAO AQUASTAT (aggregate data for all countries except Andorra and Serbia, external data), and using UN-Water category thresholds (2013).

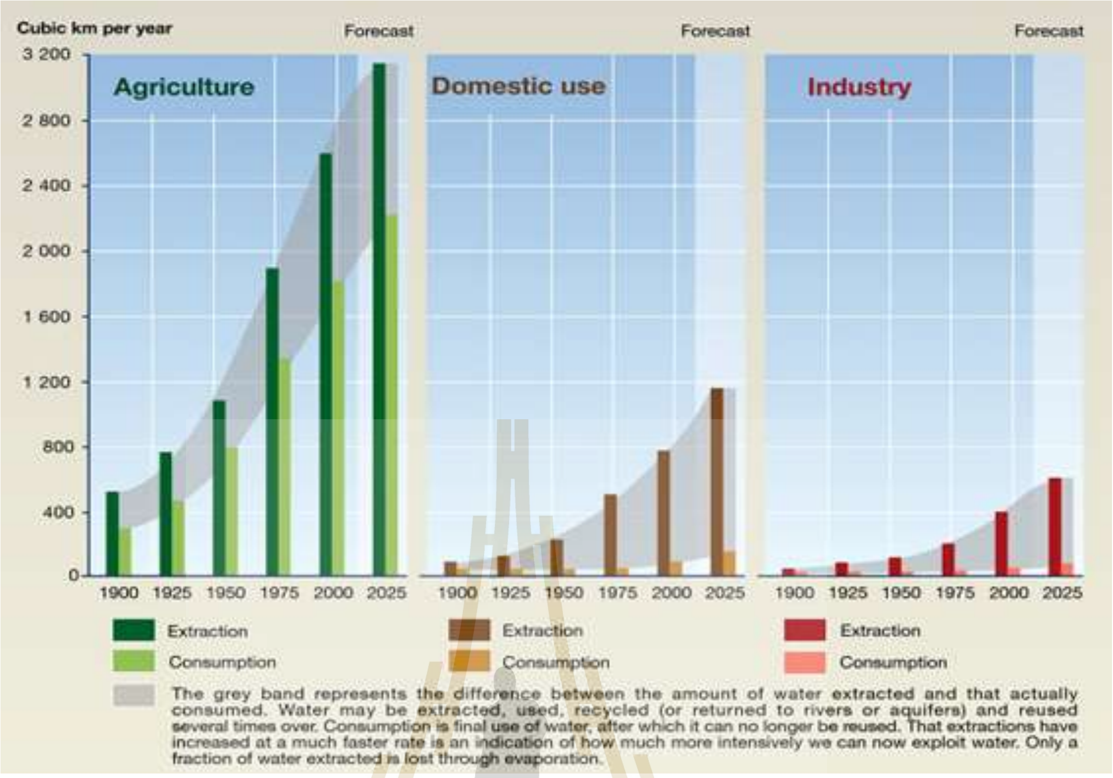


Figure 2.2 Trends in global water use by sector.

Source: United Nations Environment Programme; UNEP (2008).

Figure 2.2 shows that the agricultural sector is the biggest user of freshwater followed by the domestic and industrial sectors. According to the estimates for the year 2000, agriculture accounted for 67% of the world’s total freshwater withdrawal and 86% of its consumption (UNESCO, 2000). By 2025, agriculture sector is expected to increase its water requirements by 1.3 times, industry by 1.5 times, and domestic consumption by 1.8 times (Shiklomanov, 1999). By the year 2000, an estimated 15% of the world’s cultivated lands had been irrigated for food crops, accounting for almost half the value of global crop production (UNESCO, 1999). With regard to the industrial sector, the biggest share of freshwater is stored in reservoirs and dams for electrical power generation and irrigation. However, the volume of water evaporated from reservoirs is estimated to exceed the combined freshwater needs of industry and domestic consumption. This greatly contributes to water losses around the world, especially in hot tropical regions (UNESCO, 1999), while domestic water use is related to the quantity of water available to populations in cities and towns (UNEP, 2008).

2.1.2 Freshwater resources and demand in Thailand

Surface water resources in Thailand can be divided into 25 river basins. The average annual rainfall of the country is about 1,700 mm. The total annual rainfall of all river basins is about 800,000 million m³ out of which 75% of the amount is lost through evaporation, evapotranspiration and the remaining 25% is in streams, rivers, and reservoirs. Thus, the available water quantity was about 3,300 m³/capita/year (Sethaputra *et al.*, 2001). The data on surface water resources in Thailand is given in Table 2.1.

Table 2.1 Surface water resources in Thailand (Sethaputra *et al.*, 2001).

Region	Catchment area (km^2)	Average annual rainfall (mm/year)	Amount of rainfall (Mm^3)	Amount of runoff (Mm^3)
Northern	169,640	1,280	217,140	65,140
Central	30,130	1,270	38,270	7,650
North-eastern	168,840	1,460	246,500	36,680
Eastern	34,280	2,140	73,360	22,000
Western	39,840	1,520	60,560	18,170
Southern	70,140	2,340	164,130	49,240
Total	512,870	-	799,960	198,880

Groundwater is an important water source for Thailand. It is estimated that 75% of domestic water is obtained from groundwater sources (Sethaputra *et al.*, 2001). There are more than 200,000 groundwater wells undertaken by both the government and private sectors with a total capacity of about 7.55 million m^3/day (2,774 million m^3/year), which are mainly recharged by rainfall at about 38,000 million m^3 annually (Udomratanasilpa, 2008).

In Thailand, water required for domestic use is classified according to rural or urban areas. The water use in rural areas is estimated at 50 liters/person/day, while in urban areas it is estimated at 250 liters/person/day (Thailand National Consultation, 2013). Water required for agriculture and power-generating practices is the highest at 75.5% followed by ecological maintenance (17.6%), domestic consumption (3.5%), and industry and tourism (3.4%) (Udomratanasilpa, 2008). Most of the irrigated areas are in the Central Plain (45%), followed by the North (26%), the Northeast (17%), and the South (12%) (Doppler *et al.*, 2009). Total water demand, not including that necessary to maintain the ecological balance, is expected to increase from 57,000 Mm^3 in 2004 to 77,000 million m^3 in 2024 (Thailand National Consultation, 2013). Water resources development processes have been started in Thailand. The concept of water security was developed to investigate the actual situation of these basic water developments, both socio-economic and environment. Koontanakulvong *et al*. (2014) presented the water security status of Thailand, compared with the world, Asia and ASEAN regions. Table 2.2 shows Thailand has strengths of clean water and sanitation water accessibility arising from investment in development in the past. However, water use status regarding renewable fresh water and the agricultural sector seem to be weak compared with other countries. Thus, for future socio-economic development, the restructuring of present water use, especially for industrial and urban use, is needed to cope with future water demand increase.

Table 2.2 Average water use status world for Asia and ASEAN and the ranking of Thailand (Koontanakulvong *et al.*, 2014).

Items	Elements	World		Asia		ASEAN		Thailand
		average	rank	average	rank	average	rank	
Basic water	1. Freshwater renewable (m^3/capita)	22,167	79	10,854	15	19,205	8	6,382
	2. Water supply (m^3/capita)	84	46	84	9	85	3	98
	3. Sanitation water (m^3/capita)	67	15	70	6	71	2	96
Sufficient water	1. Water use (m^3/capita)	511	12	842	9	531	7	1,391
	2. Households (m^3/capita)	84	46	84	9	85	3	98
	3. Agricultural water (m^3/capita)	354	159	712	7	424	1	1,322
Water for development	1. Irrigation area (%)	19	49	41	30	18	3	25
	2 .Industrial water (m^3/capita)	97	68	60	18	49	4	34
	3. Water for energy (%)	31	89	20	23	14	6	4
	4. Water for fresh water aquaculture (m^3/capita)	346,734	4	1,241,323	4	582,458	2	1,385,801
Water disaster	1. Flood damage (US$)	3,543,108	3	8,670,092	2	6,002,888	1	41,051,592
	2. Drought damage (US$)	1,261,531	22	1,896,770	5	239,512	2	424,300
Water for future	1. Population growth (%)	1.3	137	1.43	38	1.31	10	0.43
	2. Urban population growth (%)	63	147	59	30	59	7	42
	3. Water footprint (m^3/capita)	1,338	7	1,304	2	1,697	2	2,223
Water productivity	1.GDP (million US$)	343,530	29	445,799	7	151,224	2	318,907
	2. Productivity (US$/$m^3$ of water)	81	132	41.3	132	117.3	6	3.6
	3. Agricultural productivity (US$/$m^3$ of water)	392	124	33.8	18	162.5	7	0.32
	4. Industrial productivity (US$/$m^3$ of water)	169.1	63	69.5	8	121.6	4	51.2

The agricultural sector is the most effected by water scarcity. Irrigation intensity is low throughout Thailand, despite agricultural development of irrigation projects that have been implemented throughout the country for over fifty years. The agricultural water resources development and management are of utmost importance as Thailand is dependent on its agriculture for food security, rural development, and economic stability. A decrease of available and suitable water for irrigation could place serious restraints on Thailand’s crops and farming. Best water management practices are integral to optimizing agricultural yields and ensuring adequate water availability for future needs (Sethaputra *et al.*, 2001; Aaroe *et al.*, 2011).

2.2 Water footprint theory

Water plays a key role in life on our planet. It is essential not only for direct uses such as for the provision of drinking water, growing food and the production of energy and other products, but also for ensuring the integrity of ecosystems and the goods and services they provide to humans (Ercin *et al.*, 2012). Thus, the water footprint (WF) offers a perspective on how a consumer or producer relates to the use of freshwater systems.

2.2.1 Water footprint concept

The WF is part of a family of footprint concepts. The WF concept was introduced to create a consumption-based indicator of water use (Hoekstra and Hung, 2004; Hoekstra and Chapagain, 2007). WF is primarily rooted in the desire to illustrate the hidden links between human consumption and water use and between global trade and water resources management (Ercin and Hoekstra, 2012). The WF is defined as the volume of water used to produce the goods and services consumed by the inhabitants of a country (Hoekstra and Chapagain, 2004). The framework of WF looks at direct and indirect water use of a consumer or producer. WF can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measures of water withdrawal (Hoekstra *et al.*, 2011).

The WF can be divided into an internal and an external WF. The internal component covers the use of domestic water resources and the external component covers the use of water resources elsewhere (Kampman, 2007). Furthermore, agricultural, industrial, domestic consumption and global commodities trade components of the WF can be assessed. The virtual water content (VWC) can be defined as the water required for manufacturing a product or a service, which refers to the water embedded in a product or service. Water is directly consumed in manufacturing operations and indirectly throughout the supply chain (Hoekstra *et al.*, 2009). Virtual water also contains the actual amount of water that exists in certain products, particularly since this water is also necessary for the production of these goods (Schubert, 2011). Hence, the VWC is known as the water productivity of a commodity. For VWC, the production and its trade flow can be translated into water use in products and the virtual water flow (VWF) which is related to the trade of a commodity.

2.2.2 Categories of water footprint

The WF refers to both consumptive water use (of rainwater), and of surface and ground water and degradative and degenerative water use. The WF assessment was introduced by Hoekstra *et al.* (2011), and can be classified into three groups: green, blue and grey components, according to direct and indirect water use as mentioned in Figure 2.3.

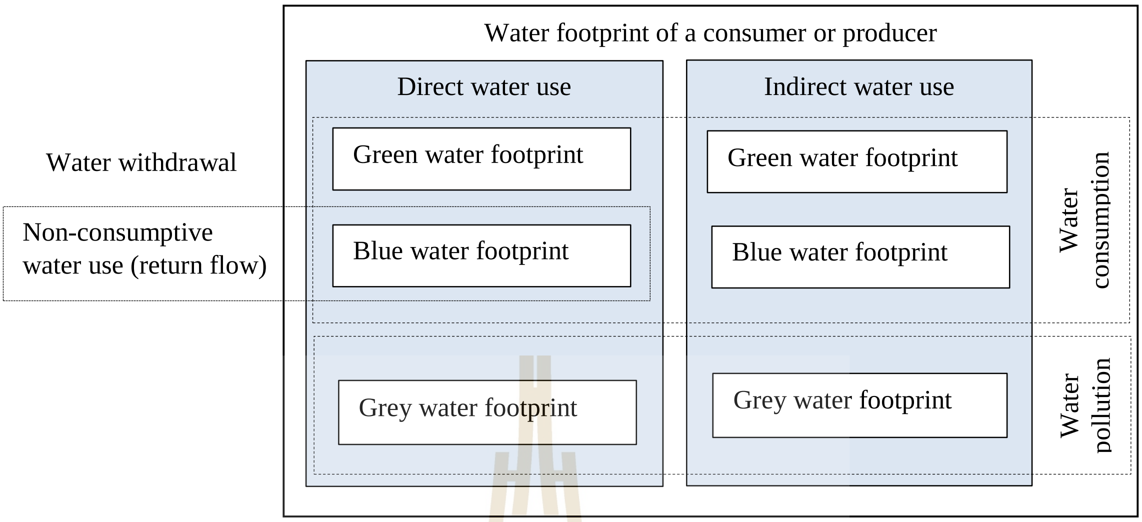


Figure 2.3 The components of a water footprint.

Source: Hoekstra *et al*. (2011).

2.2.2.1 Direct and indirect water use

Direct water use of a consumer or a producer refers to the freshwater consumption and pollution that is associated with water use by the consumer or a producer (direct water use of a consumer: e.g., the water used at home or in the garden; direct water use of a producer: e.g., water use for producing, manufacturing and supporting activities). Indirect water use refers to the water used in the production and supply chains of the goods and services consumed by the consumer or producer. Moreover, Hoekstra (2012) explained the direct WF of production, which refers to the water consumption in the product step, and also an indirect WF, which refers to the water consumption in the previous steps. In Figure 2.4, Hoekstra (2012) illustrated direct and indirect WF in each stage of the supply chain of an animal product which starts with feed crop cultivation and ends with the consumer.

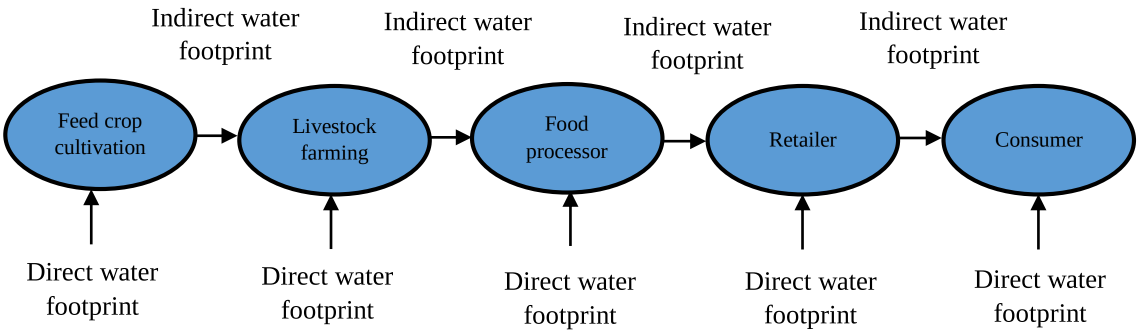


Figure 2.4 The direct and indirect water footprint in each stage of the supply chain of an animal product.

Source: Hoekstra (2012).

2.2.2.2 Consumptive and non-consumptive water use

A WF takes into account merely consumptive water use, which is water that is evapotranspirated, incorporated into a product or returned to a different watershed from which it is extracted, or returned at a different time. However, WF excludes non-consumptive water use or water withdrawal, which is returned to the same watershed and is available for downstream uses.

2.2.2.3 The green, blue and grey water footprint

1) The green water footprint

The green WF is the volume of water evaporated from green water resources (the rainwater is stored in the soil, so it does not become run-off). It is particularly relevant to agricultural or horticultural and forestry products. The total green water includes evaporation and transpiration during production, plus the water incorporated into the harvested crop or wood.

2) The blue water footprint

The blue WF is the volume of freshwater consumption that is evaporated or incorporated from blue water resources (surface and groundwater) into a product and returned to another catchment or a sea, or returned at a different period. Blue water generally refers to water that can be delivered for irrigation or made available for alternative uses.

3) The grey water footprint

The grey WF is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations, which is quantified as the volume of water required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards. For cultivated crops, it is the volume of water dilution required to reduce chemical leaching from agreed fertilizers and pesticides standards to acceptable levels.

For green and blue water, blue water generally refers to water that can be delivered for irrigation or made available for alternative uses, while green water must be used directly from the soil profile (Wichelns, 2010). The opportunity costs of blue water use are generally higher than green water use, because blue water has a number of alternative uses. In addition, blue water has a supply cost, since it has to be pumped and transported through pipes or irrigation equipment before being applied to the crops. If a grower is paying the correct price for water, then their choice of crop would need to reflect a higher added-value, in order to cover the costs of using this water

(Chapagain and Orr, 2009; Herath, 2013). The distinction between blue and green water is important, since green water is only available for use by plants at the precise location where it occurs, while blue water is available generally for use in a wide range of systems, which are managed by human, but not limited to, water use by plants (Canals *et al.*, 2009; Herath, 2013).

2.2.2.3 The water footprint case studies

WF case studies have been completed for a variety of entities, including countries, products, commodities and river basins. The country and river basin WF focus on informing policy, whereas the product, and commodity WF focus on understanding supply chain risks. Different potential uses and challenges exist for each type of study (Hastings and Pegram, 2012).

1) Country

The first WF studies focused on illustrating water flows between countries through trade of industrial and agricultural products. These studies are useful in illustrating virtual water flows into and out of countries. However, the local context of water use must be included to understand the impacts, and challenges arise in framing the WF as it is only one of many environmental, social and economic indicators that must be considered in the context of trade.

2) Basin

Basin-level WF has gained focus in recent years. Basin WF is largely directed to the public sector, with the intent to foster strategic dialogue, inform sector policy and development planning, or inform water allocation. However, it has proven difficult to contextualize the WF and to integrate a WF with the wide spectrum of public interests and the complex political decision-making processes. Basin-level WF has been a useful communication tool for fostering dialogue between diverse sectors.

3) Product

Following country-level WF, companies began using WF to help understand the footprint of products. International reviews show that WF has different levels of traction for different industries. The food, beverage and textiles sectors are most active with WF, as the tool helps to understand significant upstream supply chain risks. Consumer products and cosmetics, which have significant downstream water implications, are becoming of increasing interest. The chemicals and mining industries have been least active with WF. In the studies completed, WF is perceived as being useful for understanding supply chain water risk, and for benchmarking and communication. However, there is concern as to whether grey water is an appropriate representation of water quality. Additionally, understanding the local context of water use, as well as the social, economic and environmental considerations, is both a critical and difficult task.

4) Commodity

WF has also been studied for global commodities and markets, such as wheat, cotton or biofuels. Commodity WF is useful for illustrating virtual water flows through trade between countries, and can help companies understand supply chain risks and make informed decisions. Additionally, commodity WF can create transparency and provide information, which allows the public to hold companies accountable for supply chain decisions. Again, understanding the local context, including economic and social factors, is critical to understanding impacts.

2.2.3 Water footprint assessment

The WF assessment is the full range of activities to: (i) quantify and locate the WF of a process, product, producer or consumer or to quantify in space and time the WF in a specified geographic area; (ii) assess the environmental, social and economic sustainability of this WF; and (iii) formulate a response strategy. It is an analytical tool, it can be instrumental in helping to understand how activities and products relate to water scarcity and pollution and related impacts and what can be done to make sure activities and products do not contribute to unsustainable use of freshwater (Hoekstra *et al*., 2011).

The WF assessment consists of a four-phase process (Figure 2.5) that quantifies and maps green, blue and grey WFs, assesses the sustainability, efficiency and equitability of water use and identifies which strategic actions should be prioritized in order to make a footprint sustainable.

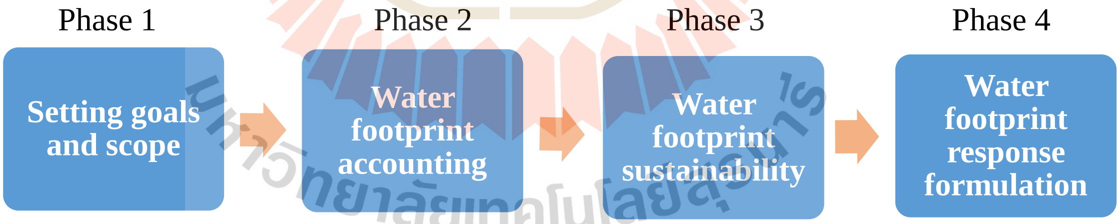


Figure 2.5 The four-phase process of water footprint assessment.

Source: Hoekstra *et al*. (2011).

2.2.3.1 Setting goals and scope

The WF Assessment begins with setting the goals and scope of the study. It is the first and an important step to clarify the purpose of WF assessment. A WF study can be undertaken for many different reasons. It can be undertaken for diverse purposes. For example, it can be undertaken to (Water footprint network, 2015):

1) Support a specific business on achieving sustainable water management within their direct operations and supply chain.

2) Support governments and regulatory agencies on national or regional sustainable water allocations and management.

3) Define benchmarks for water consumption and water pollution for a specific sector of activity or production of a specific product.

4) Raise awareness on water sustainability issues related to water use.

The goal of the WF assessment clarifies what we will do in the subsequent steps: accounting, sustainability assessment and response formulation. The scope of the assessment defines the spatial and temporal scale of the study, for example, whether the focus will be global or within a single catchment, whether it will span one year or multiple years, whether it will include some or all of the value chain, address one product or a facility or an entire company. Together, the goal and scope indicate which data will be used, how each subsequent step of the assessment will be approached and the level of detail required to achieve the desired results. Furthermore, the goal of WF assessment studies may have various purposes and be applied in different contexts. Each purpose requires its own scope of analysis and will allow for different choices when making assumptions: for instance, in Hoekstra *et al*. (2011):

1) Water footprint of a process step
2) Water footprint of a product
3) Water footprint of a consumer

4) Water footprint of a group of consumers (consumers in a nation, consumers in a municipality, consumers in a catchment area or river basin)

5) Water footprint within a geographically delineated area (within a nation, with in a municipality, within a catchment area or river basin)

6) Water footprint of a business

7) Water footprint of a business sector

8) Water footprint of humanity as a whole

2.2.3.2 Water footprint accounting

One will have to be clear and explicit about the 'inventory boundaries' when setting up a WF account. The inventory boundaries refer to 'what to include' and 'what to exclude' from the accounts and should be chosen as a function of the purpose of the account. WF accounting is the step of calculating the green, blue and grey components. Blue water resources are generally scarcer and have higher opportunity costs than green water, so that may be a reason to focus on accounting for the blue WF only. However, green water resources are also limited and thus scarce, which gives an argument to account for the green WF as well (Falkenmark, 2003; Rockström, 2001). The idea of the grey WF was introduced in order to express water pollution in terms of a volume polluted, so that it can be compared with water consumption (Chapagain *et al*., 2006; Hoekstra and Chapagain, 2008). If one is interested in water pollution and in comparing the relative claims of water pollution and water consumption of the available water resources, it is relevant to account for the grey in addition to the blue WF. The methodology and calculation of WF and their components that are relevant processes for this study are given below in 2.2.4-2.2.6.

2.2.3.3 Water footprint sustainability

Sustainability science explores the interactions between human activities on the Earth's life support systems (Rockstrom *et al*., 2009). Focusing on water as a key resource for human and ecosystem health, for which sustainability assessment is needed in order to preserve its quality and quantity for present and future generations (Sala *et al*., 2013). In the case of a geographic perspective, it will look at the sustainability of the aggregated WF in a certain area, preferably a catchment area or a whole river basin, while in the case of a process, product, consumer or producer perspective, the focus is not on the aggregate WF in one geographic setting, but on the contribution of the WF to the individual process, product, consumer or producer (Hoekstra *et al*., 2011). The sustainability assessment step assesses mainly three purposes including environmental sustainability, resource efficiency and equitable allocation (Water footprint network, 2015);

1) Environmental sustainability

With regard to environmental sustainability, water use must not exceed the maximum sustainable limits of a freshwater resource. We use blue water scarcity to measure the environmental sustainability of the blue WF. It is the measure of the blue WF compared to the water available after considering environmental flow requirements. When the blue WF is larger than the available water, environmental flows are not met and over time, freshwater ecosystems will be degraded. Grey WF is a tool to measure the water pollution level. If the grey WF exceeds the assimilation capacity, the water quality standards are violated and the quality of the water will not meet socially agreed upon purposes. Blue water scarcity and water pollution levels are used to assess the cumulative impact of all water uses of freshwater resources.

2) Resource efficiency

The WF is an ideal measure of resource efficiency because it can be measured per unit of production, for example, the number of cubic meters required to produce a ton of wheat. As the WF goes down, this indicates a more efficient use of water in producing wheat or any other product. If the WF exceeds a benchmark of resource efficiency for that activity, this indicates that there is the opportunity for WF reduction through a change in practices or technology.

3) Equitable allocation

Equitable allocation means that the allocation of the WF within a river basin is a fair allocation between different water users and different sectors (WF allocation between users and consumers) in a way that benefits greater societal goals. It can also mean that no individual, community or country has a larger WF associated with the products and services they consume than others.

Additionally, the scope of a WF sustainability assessment purpose is to investigate for geographic perspective. When considering the WF of production for a basin or catchment, water inputs to that product must be identified, and a sustainability assessment must be undertaken for each geographic area. The steps identified for the sustainability assessment are (Hastings and Pegram, 2012):

1) Identification of the environmental (green, blue and grey WFs), social (drinking water, food security, employment) and economic sustainability (value of water in the economy) criteria.

2) Identification of hotspots, including particular catchments and times of the year.

3) Identification and quantification of the primary or direct impacts on the hotspots.

4) Identification and quantification of the secondary, or indirect, impacts on the hotspots.

A 'hotspot' is a catchment where the total WF is unsustainable for a period of the year according to the environmental, social and economic criteria identified. Thus, a sustainability assessment seeks to identify the location at a catchment-level where water use or pollution exceeds which is deemed acceptable to meet environmental, social and economic standards. It then quantifies the impact in that catchment.

2.2.3.4 Water footprint response formulation

The final step in WF assessment is to form a response to the WF. In theory, if a WF is deemed not sustainable, action should be taken to reduce the WF and make it sustainable. The suite of responses possible will depend on the entity or group responding. The entity which will be responding should be identified in the goal-setting phase of the WF, and may include consumers, companies, investors or government. What constitutes an appropriate response or suite of responses is in the very early stages of development. Many ideas for responses have been suggested for consumers, companies, government and investors. For example, farmers and agricultural policy can seek to support efficient farming practices, and retailers or food and beverage companies can engage with their supply chains to encourage efficient practices.

However, these suggestions are very simplified. It is unclear how a WF should actually inform the choice of which response is most appropriate, and what makes these responses different from generally good water management practices, so efforts are underway to develop an understanding of the response options (Hastings and Pegram, 2012).

2.2.4 Water footprint of crop cultivation

The largest use of water resources is associated with growing and producing food. Many food products contain ingredients from crops and animals. The agriculture sector then in fact accounts for major water consumption which is an important part in thinking about where and how much water use is required to produce their ingredients.

The WF of a crop cultivation is estimated by following by The Water Footprint Assessment Manual as introduced by Hoekstra *et al.* (2011), and calculating the WF into green, blue and grey WFs. The total WF of crop production is the sum of these three components as shown in the following equation:

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \quad \text{---------------} \ (2.1)$$

The WF of a crop is generally expressed in terms of volume per mass such as m^3/ton or liter/kg.

2.2.4.1 The green and blue water footprints of a crop cultivation

How to calculate the green and blue WFs of a crop by following the calculation framework of Hoekstra *et al.* (2009) is illustrated in the following equation:

$$\mathrm{WF}_{\mathrm{green,blue}} = \frac{\mathrm{CWU}_{\mathrm{green,blue}}}{\mathrm{Y}} \quad \text{----------------- (2.2)}$$

$$= \frac{10 \times \sum_{\mathrm{d=1}}^{\mathrm{lgp}} \mathrm{ET}_{\mathrm{green,blue}}}{\mathrm{Y}} \quad \text{----------------- (2.3)}$$

Where the green or blue WFs; $\mathrm{WF}_{\mathrm{green}}$ or $\mathrm{WF}_{\mathrm{blue}}$ (in volume/mass) is calculated as crop water use; CWU (in volume/area) divided by the crop yield; Y (in mass/area), while CWU with both green and blue shows the accumulation of daily crop evapotranspiration; ET (in mm/day) over the complete growing period. A factor of 10 is applied to convert the unit from mm into m^3/ha. The lgp indicates the length of the growing period from the day of planting to the day of harvest.

1) Corp evapotranspiration

Calculating the WF of crop products according to the following equation (2.3), the ET and yield required for the estimation of the $\mathrm{WF}_{\mathrm{green}}$ and $\mathrm{WF}_{\mathrm{blue}}$ have been carried out by following the method and assumptions provided by Allen *et al*. (1998), which was published by the Food and Agriculture Organization of the United Nations (FAO). The evapotranspiration process takes place when water is lost from the soil surface by evaporation and from the crop through transpiration.

Evaporation is the process by which liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (vapor removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Additionally, transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere. The evapotranspiration rate is normally expressed in mm per unit of time. The rate expresses the amount of water lost from a cropped surface in units of water depth. The ET depends on the three main factors which are climate parameters (which determine potential evapotranspiration), crop characteristics and soil water availability (Allen *et al*., 1998) as shown in the following equation:

$$\mathrm{ET_c[t] = K_c[t] \times ET_o[t]} \qquad \text{---------------- (2.4)}$$

$$\mathrm{ET_{c\,adj}[t] = K_c[t] \times K_s[t] \times ET_o[t]} \qquad \text{---------------- (2.5)}$$

Where ET_c is the crop evapotranspiration under standard conditions, $ET_{c\ adj}$ (some references call this ET_a) is the crop evapotranspiration under non-standard conditions. The $K_c[t]$ is the crop coefficient, $K_s[t]$ is a dimensionless transpiration reduction factor dependent on available soil water and $ET_o[t]$ is the reference evapotranspiration (in mm/day). The crop coefficient varies in time, as a function of the stage of plant growth.

The climatic parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed. The evaporation power of the atmosphere is expressed by the ET_o. The ET_o represents the evapotranspiration from a standardized vegetated surface.

Crop characteristics, the differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different evapotranspiration levels in different types of crops under identical environmental conditions. The ET_c under standard conditions refers to the evaporating demand from crops that are grown in large fields under optimum soil water, excellent management and environmental conditions, and achieve full production under the given climatic conditions. For the $ET_{c\ adj}$ under non-standard conditions, the soil water availability, factors such as soil salinity, poor land fertility, limited application of fertilizers, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration. Other factors are ground cover, plant density and the soil water content. The effect of soil water content on ET is conditioned primarily by the magnitude of the water deficit and the type of soil.

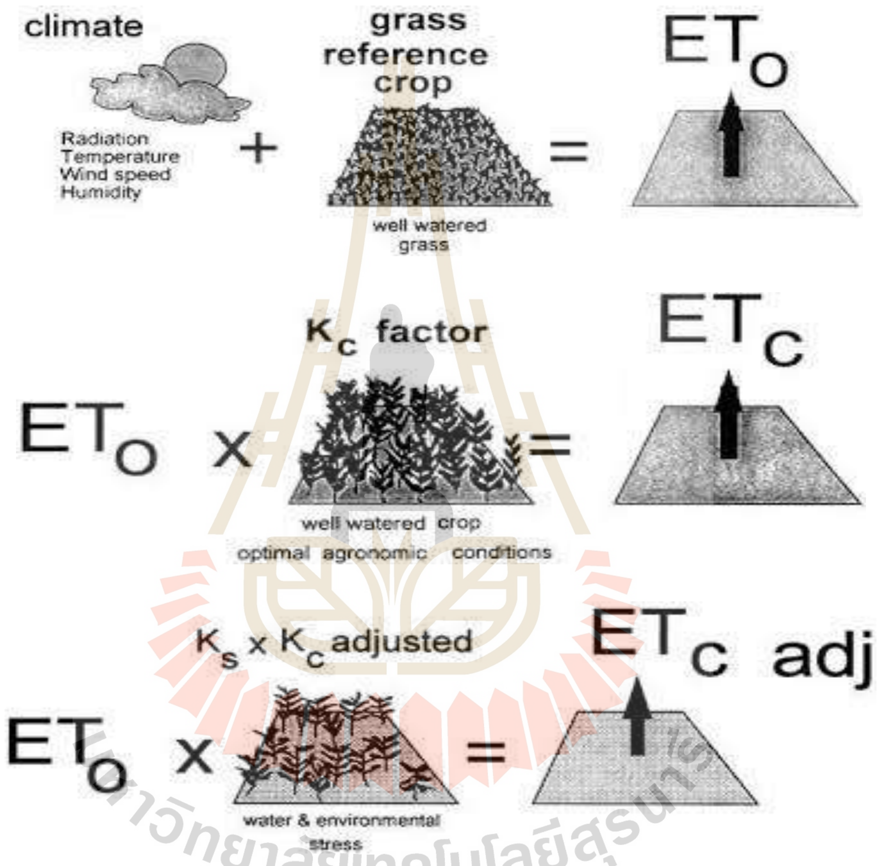


Figure 2.6 Reference crop evapotranspiration, crop evapotranspiration under standard conditions and non-standard conditions.

Source: Allen *et al*. (1998).

- Reference crop evapotranspiration (ET_o)

The evapotranspiration rate from a reference surface which is not short of water is called the ET_o. The reference surface is a hypothetical grass reference crop with specific characteristics. The concept of the ET_o described by Allen *at al.* (1994) was introduced in a clear definition to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the reference evapotranspiring surface, soil factors do not affect evapotranspiration. Relating evapotranspiration to a specific surface provides a reference to which evapotranspiration from other surfaces can be related. It obviates the need to define a separate evapotranspiration level for each crop and stage of growth. The ET_o values measured or calculated at different locations or in different seasons are comparable as it refers to the evapotranspiration from the same reference surface.

The only factors affecting ET_o are climatic parameters. As a result, ET is a climatic parameter and can be computed from weather data. ET_o expresses the evaporative demand of the atmosphere at a specific location and time of the year, and does not consider crop and soil factors. The FAO Penman-Monteith method is recommended as the sole method for determining ET_o (Allen *et al.*, 1998). This method has been selected because it closely approximates grass ET_o at the location evaluated which is physically based and explicitly incorporates both physiological and aerodynamic parameters. Calculation procedures to derive climatic parameters from meteorological data and to estimate missing meteorological variables required for calculating ET_o are presented in Chapter III. Nevertheless, ET_o can also be estimated from pan evaporation. Pans have proved their practical value and have been used successfully to estimate ET_o by observing the water loss from the pan and using empirical coefficients to relate pan evaporation to ET_o. However, special precautions and management must be applied.

- Crop evapotranspiration under standard conditions

The ET estimated under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. The amount of water required to compensate for the evapotranspiration loss from the cropped field is defined as crop water requirement (CWR). Although the values for ET and CWR are identical. The ET refers to the amount of water that is lost through evapotranspiration, while the CWR refers to the amount of water that needs to be supplied. The irrigation water requirement basically represents the difference between the CWR and effective precipitation. The irrigation water requirement also includes additional water for leaching of salts and to compensate for non-uniformity of water application.

In equation 2.4, the crop coefficients (K_c), are used to relate ET_c to ET_o. K_c is the ratio of the crop ET_c to the reference ET_o, while ET_c under standard conditions represents the upper envelope of crop evapotranspiration and conditions where no limitations are placed on crop growth or evapotranspiration due to water shortage, crop density, or disease, weeds, insects or salinity pressures. The effects and characteristics that distinguish field crops from grass are integrated into K_c. The major factors determining K_c are crop variety, climate and stage of crop growth.

To determine the length of the crop growth stages and the corresponding crop coefficients, it is necessary to take into account the crop coefficient curve which represents the changes in the crop coefficient over the length of the growing season. The shape of the curve represents the changes in the vegetation and ground cover during plant development and maturation that affect the ratio of ET_c to ET_o (as shown in Figure 2.7)

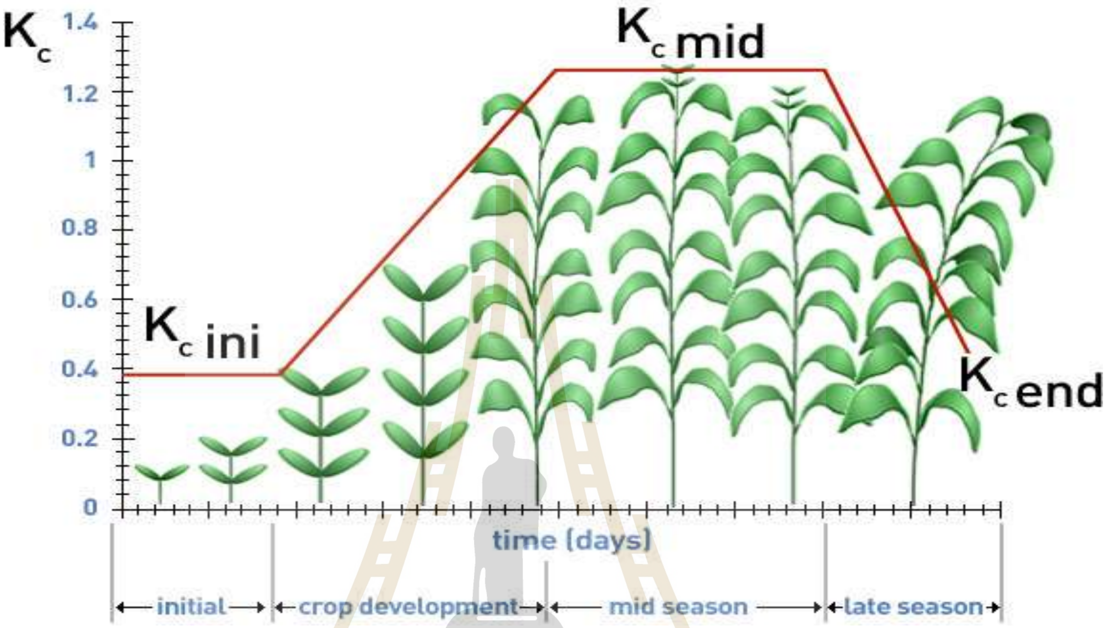


Figure 2.7 The variation in the crop coefficient (K_c).

Source: Allen *et al*. (1998); http://www.fao.org/nr/water/cropinfo_tomato.html.

Due to the differences in evapotranspiration during the various growth stages, the K_c for a given crop will vary over the growing period. The growing period can be divided into four distinct growth stages: initial, crop development, mid-season and late season as follows;

- In the initial stage, the length of the initial period is highly dependent on the crop, the crop variety, the planting date and the climate. The end of the initial period is determined as the time when approximately 10% of the ground surface is covered by green vegetation. The K_c during the initial period ($K_{c\ ini}$) is large when the soil is wet from irrigation and rainfall and is low when the soil surface is dry.

- Crop development stage

The crop development stage runs from 10% ground cover to effective full cover. Effective full cover for many crops occurs at the initiation of flowering. K_c value corresponds to amounts of ground cover and plant development. Typically, if the soil surface is dry, $K_c = 0.5$ which corresponds to about 25-40% of the ground surface covered by vegetation due to the effects of shading and due to microscale transport of sensible heat from the soil into the vegetation. A $K_c = 0.7$ which often corresponds to about 40-60% ground cover. These values will vary, depending on the crop, frequency of wetting and whether the crop uses more water than the reference crop at full ground cover

- Mid-season stage

The mid-season stage runs from effective full cover to the start of maturity. The start of maturity is often indicated by the beginning of the ageing, yellowing or senescence of leaves, leaf drop, or the browning of fruit to the degree that the crop evapotranspiration is reduced relative to the ET_o. At this stage, the K_c reaches its maximum value. The value for $K_{c\ mid}$ is relatively constant for most growing and cultural conditions. Deviation of the $K_{c\ mid}$ from the reference value “1” is primarily due to differences in crop height and resistance between the grass reference surface and the agricultural crop and weather conditions.

- Late season stage

The late season stage runs from the start of maturity to harvest or full senescence. The K_c value at the end of the late season stage ($K_{c\ end}$) reflects crop and water management practices. The $K_{c\ end}$ value is high if the crop is frequently irrigated until harvested fresh. If the crop is allowed to senesce and to dry out in the field before harvest, the $K_{c\ end}$ value will be small. Senescence is usually associated with less efficient stomatal conductance of leaf surfaces due to the effects of ageing, thereby causing a reduction in K_c.

- Crop evapotranspiration under non-standard conditions

The ET estimated under non-standard conditions ($ET_{c\ adj}$) is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions. When cultivating crops in fields, the real crop evapotranspiration may deviate from ET_c, due to non-optimal conditions such as the presence of pests and diseases, soil salinity, low soil fertility, water shortage or waterlogging. This may result in scanty plant growth, low plant density and may reduce the evapotranspiration rate below ET_c. The ET under non-standard conditions is calculated by using a water stress coefficient K_s and/or by adjusting K_c for all kinds of other stresses and environmental constraints on crop evapotranspiration (as shown in equation 2.5). The K_s describes the effect of water stress on crop transpiration. For soil water limiting conditions, $K_s < 1$; where there is no soil water stress, $K_s = 1$ (Allen *et al.*, 1998).

2) Estimation of the crop evapotranspiration

The ET is also divided into two components, which is green and blue evapotranspiration and these can be estimated by using the CROPWAT 8.0 program. This program computes two different options to calculate the ET: the CWR-option and the irrigation schedule-option. The CWR-option is the simplest but not the most accurate, for which it is assumed that there are no water limitations to crop growth. This option can be used to estimate the ET_c (the value is equal to the crop water requirement). The ET_c can be calculated by running the CWR-option in the CROPWAT 8.0 program with climate and crop characteristics alone, which is estimated with a ten-day time step and over the total growing season using the effective rainfall: P_{eff}. The P_{eff} is a part of the total amount of precipitation that is retained by the soil so that it is potentially available for meeting the water needs of the crop. It is often less than the total rainfall because not all rainfall can actually be appropriated by the crop and the intensity of rain may be such that part of the rainfall is lost due to surface runoff or due to deep percolation below the root zone. The P_{eff} can be calculated by the method of the Soil Conservation Service of the United States Department of Agriculture (USDA, SCS), described in an FAO publication, which implemented the CROPWAT 8.0 program (FAO, 2013b) using the following equation:

$$P_{eff} = P\frac{125-0.2P}{125} \qquad \text{for } P \leq 250 \text{ mm/month} \quad \text{----------------} \ (2.6)$$

$$P_{eff} = 125 + 0.1P \qquad \text{for } P > 250 \text{ mm/month} \quad \text{----------------} \ (2.7)$$

Where P is the gross monthly rainfall and the units used are in millimeters. Equation 2.6 is used when the gross rain is equal or less than 250 millimeters and equation 2.7 is used if the gross rainfall is greater than 250 millimeters

The irrigation requirement (IR) is calculated as the difference between the crop water requirement and the effective rainfall. The IR is zero if the P_{eff} is larger than the CWR. It is assumed that the IR conditions are fully met.

The green water evapotranspiration is ET_{green}, which is evapotranspiration of rainfall, and which can be equated with the minimum between ET_c and P_{eff}. Blue water evapotranspiration is ET_{blue}, which is field-evapotranspiration during irrigation, and is the difference between the ET_c and P_{eff}, but it is zero when effective rainfall exceeds crop evapotranspiration. This can be expressed as follows:

$$\mathrm{ET_{green}} = \min(\mathrm{ET_c}, \mathrm{P_{eff}}) \quad \text{----------------} \ (2.8)$$

$$\mathrm{ET_{blue}} = \max(0, \mathrm{ET_c} - \mathrm{P_{eff}}) \quad \text{----------------} \ (2.9)$$

The second is the irrigation schedule-option. It is recommended that the option be applied whenever possible because it is applicable to both standard and non-standard conditions because it is more accurate as the underlying model and includes a dynamic soil water balance (Hoekstra *et al*, 2011). The calculation of crop evapotranspiration is called $ET_{c\ adj}$, but in this report ET_a is used. The ET_a might be smaller than ET_c due to non-standard conditions because of the water movements in the soil, the water holding capacity of the soil and the ability of the plants to use the water which can be influenced by different factors such as physical conditions, fertility and the biological status of the soil. Hence, the water stress coefficient (K_s) impacts only on crop transpiration rather than evaporation from soil (Allen *et al.*, 1998) as shown in the equation 2.5. To estimate the ET_{green} and ET_{blue} in irrigated agriculture, after inputting the climatic data, crop characteristics and soil data the CROPWAT 8.0 program can be run with the selected irrigation options, where ET_a over the growing period is equal to what is called the ‘actual water used by crop’ in the program output. The ET_{blue} is equal to the minimum ‘total net irrigation’ and ‘actual irrigation requirement’ as specified in the program output. The ET_{green} is equal to the ET_a minus the ET_{blue} as simulated in the irrigation scenario.

2.2.4.2 The grey water footprint of a crop

The methodology and calculation of the grey WF is described in The Water Footprint Assessment Manual written by Hoekstra *et al*. (2011) and in Grey Water Footprint Accounting introduced by Franke *et al*. (2013). The WF_{grey} of crop products is an indicator of the amount of freshwater pollution that can be associated with activities in the crop field. It is calculated by dividing the pollutant load entering a water body; L (in mass/time) by the critical load; L_{crit} (in mass/time) times the runoff of the water body times; R (in volume/time):

$$WF_{grey} = \frac{L}{L_{crit}} R \qquad \text{--------------- (2.10)}$$

Where the critical load is the load of pollutants that will fully consume the assimilation capacity of the receiving water body. It can be calculated by multiplying the leaching-runoff of the water body; R (in volume/time) by the difference between the ambient water quality standard of the pollutant (the maximum acceptable concentration which is C_{max}, in mass/volume) and its natural background concentration in the receiving water body (natural background concentration = C_{nat}, in mass/volume). Finally, the WF_{grey} of its crop production is then divided by the crop yield; Y (in mass/time):

$$L_{crit} = R(C_{max} - C_{nat}) \qquad \text{--------------- (2.10)}$$

$$WF_{grey} = \frac{L/(C_{max} - C_{nat})}{Y} \qquad \text{--------------- (2.11)}$$

The WF_{grey} calculation is carried out using the ambient water quality as a standard for the receiving freshwater body (standard with respect to maximum allowable concentrations in the water bodies). The ambient water quality standard is a specific category of water quality standards, for example, drinking water quality standards, irrigation quality standards and emission standards. In addition, the natural concentration in a receiving water body (C_{nat}) is the concentration in the water body that would occur if there were no human disturbances in the catchment. Human-made chemical substances that do not naturally occur in water is C_{nat} which is equal to zero. When natural concentrations are not known precisely but are estimated to be low, for the sake of simplicity we may assume C_{nat} is also equal to zero (Franke *et al.*, 2013). The amount of chemical substances that will reach a water body (either ground or surface water) will depend on the percentage of leaching-runoff (fraction α of the chemical substances applied). There are different specific factors that influence the leaching-runoff fraction. The list of influencing factors is slightly different in chemical substance groups: nutrients, metals, and pesticides, whereby nutrients are further distinguished into nitrogen and phosphorus. The value of α in average; α_{avg} will lie somewhere in between the minimum leaching-runoff fraction; α_{min}, and the maximum leaching-runoff fraction; α_{max}. The leaching-runoff fractions for the chemical substance can be taken from Table 2.3.

Table 2.3 Leaching-runoff fractions for nutrients, metals and pesticides (Franke *et al*., 2013).

	Nutrients		Metals	Pesticides
	Nitrogen	Phosphorus		
Minimum leaching-runoff fraction (α_{min})	0.01	0.0001	0.4	0.0001
Average leaching-runoff fraction (α_{avg})	0.1	0.03	0.7	0.01
Maximum leaching-runoff fraction (α_{max})	0.25	0.05	0.9	0.1

2.2.5 Water footprint of product

The WF of a product is the volume of freshwater used to produce the product, measured over the various steps of the production chain in terms of water volumes consumed (evaporated) and polluted. It is a geographically explicit indicator that shows not only volumes of water use and pollution, but also the locations (Hoekstra, 2012). The definition of 'virtual water' is the volume of water required to produce a commodity or service (Allen *et al*., 1998). The terms virtual water content and embedded water refer to volume alone when freshwater is used directly or indirectly to produce the product or service, measured at the place where the product was actually produced. It refers to the sum of the water use in the various steps of the production chain (Chapagain and Hoekstra, 2007).

In the case of agricultural products, the WF is generally expressed in terms of m^3/ton or liter/kg. In the case of industrial products, the WF can be expressed in terms of water volume per piece. Other ways to express a product WF are, for example, water volume/kcal (for food products in the context of diets) or water volume/joule (for electricity or fuels). The WF of a product can be estimated by calculating two alternative ways with the chain-summation approach or the stepwise accumulative approach.

2.2.5.1 The chain-summation approach

The chain-summation approach is a simple production system with only one output product which rarely exists, thus a more generic way of accounting is necessary that takes in account how the water is distributed throughout a production system to the various output products that follow from that system without double counting. The WF of a product is always expressed as water volume in terms of m^3/t or L/kg. The WF of a process is expressed as water volume per unit of time. When divided by the quantity of a product that results from the process, it can also be expressed as water volume per product unit.

In this production system, the WF of product p (volume/mass) is equal to the sum of the relevant process WF divided by the production quantity of product p:

$$\mathrm{WF}_{\mathrm{prod}}[\mathrm{p}] = \frac{\sum_{\mathrm{S}=1}^{\mathrm{k}} \mathrm{WF}_{\mathrm{proc}}[\mathrm{s}]}{\mathrm{P}[\mathrm{p}]} \qquad \text{---------------} \ (2.12)$$

In which $\mathrm{WF}_{\mathrm{proc}}[\mathrm{s}]$ is the process WF of process step s (in volume/time), and P[p] is the production quantity of product p (in mass/time).

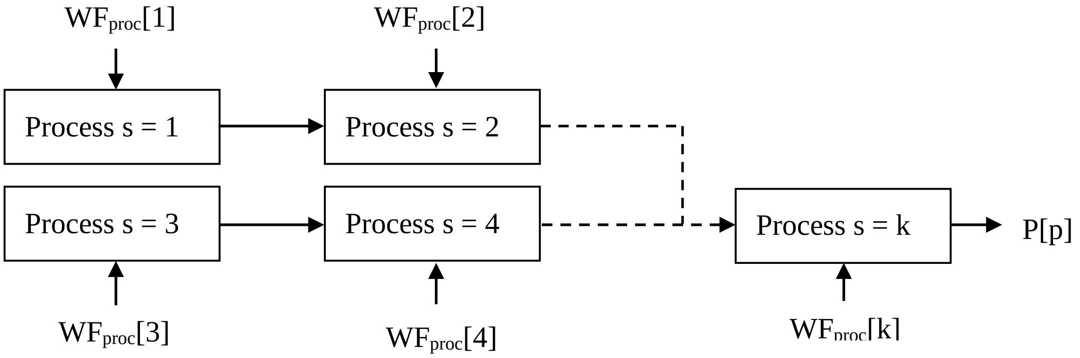


Figure 2.8 Schematization of the production system to produce product p into k process steps.

Source: Hoekstra *et al.* (2011).

2.2.5.2 The stepwise accumulative approach

The stepwise accumulative approach is a generic way of calculating the WF of a product based on the WF of the input products that were necessary in the last processing step to produce that product and the process WF of that processing step. In this case, the WF of the output product is obtained by simply summing the WF of the input products and adding the process WF. In addition, the WF of the input product to its separate products, which can be done proportionally to the value of the output products. It can also be done proportionally to the weight of the products, but this would be less meaningful. Finally, we can consider the most generic case (Figure 2.9). To calculate the WF of a product p, which is being processed from y input products, the input products are numbered from i=1 to y. Suppose that processing of the y input products results in z output products. The output products are numbered from p=1 to z.

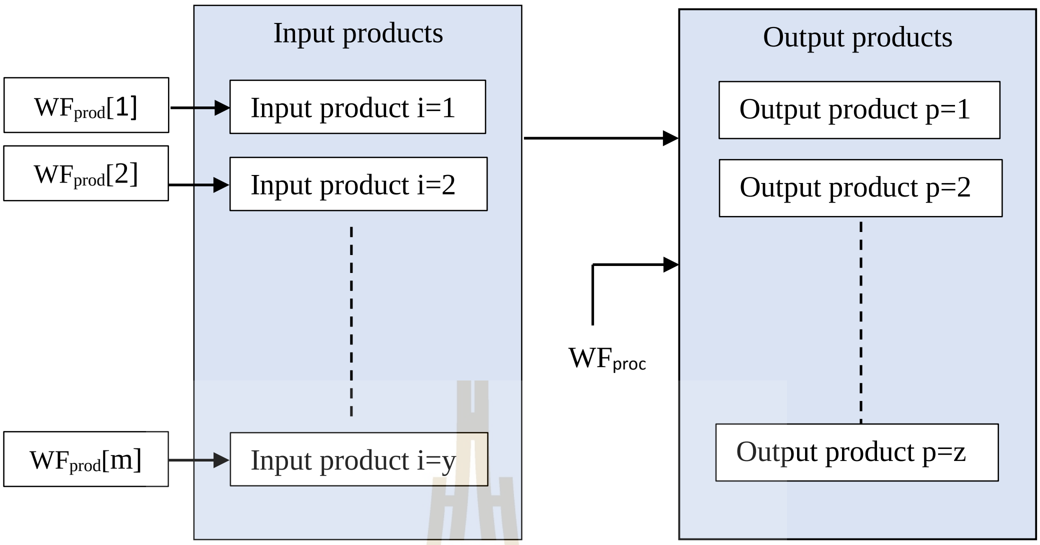


Figure 2.9 Schematization of the last process step in the production system to produce product p.

Source: Hoekstra *et al.* (2011).

The process WF is added to the WFs of the input products before the total is distributed over the various output products. The WF of the output product p is calculated as shown in the following equation:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]}\right) \times f_v[p] \quad \text{---------} \ (2.13)$$

In which $WF_{prod}[p]$ is the WF (in volume/mass) of output product p, $WF_{prod}[i]$ is the WF of input product i and $WF_{proc}[p]$ is the process WF of the processing step that transforms the y input products into the z output products, expressed in water use per unit of processed product p (in volume/mass). Parameter $f_p[p,i]$ is a so-called ‘product fraction’ and parameter $f_v[p]$ is a ‘value fraction’.

The product fraction of an output product p that is processed from an input product i ($f_p[p,i]$, in mass/mass) is defined as the quantity of the output product (w[p], in mass) obtained per quantity of input product (w[i], in mass):

$$f_p[p,i] = \frac{w[p]}{w[i]} \qquad \text{---------------} \ (2.14)$$

The value fraction of an output product p ($f_v[p]$, in monetary unit/monetary unit) is defined as the ratio of the market value of this product to the aggregated market value of all the outputs products (p=1 to z) obtained from the input products:

$$f_v[p] = \frac{price[p] \times w[p]}{\sum_{p=1}^{z}(price[p] \times w[p]} \qquad \text{---------------} \ (2.15)$$

In which price[p] refers to the price of product p (in monetary unit/mass). The denominator is summed over the z output products (p=1 to z) that originate from the input products. Note that taking 'price' here as an indicator of the economic value of a product, which is not always the case, e.g. when there is no market for a product or when the market is distorted.

In a simple case, where we process just one input product into one output product, the calculation of the WF of the output product becomes rather simple (in volume/mass):

$$WF_{prod}[p] = WF_{proc}[p] + \frac{WF_{prod}[i]}{f_p[p,i]} \qquad \text{---------------} \ (2.16)$$

2.2.6 Virtual water flow of trade

The water that is used in a production process of agricultural or industrial product is called the 'virtual water' contained in the product. Virtual water flow (VWF) of trade shows the importance of virtual water analysis in drafting national water policy plans (Chapagain and Hoekstra, 2003). The VWF between nations can relieve the pressure on scarce water resources and contribute to the mitigation of water scarcity at both local and global levels. VWF should be encouraged to promote water savings for arid countries and at global level through enhancing food security by appropriate agreements and increasing reciprocity in agricultural products trade (Hoekstra, 2003). When a country exports a water-intensive product to another country, it exports water in virtual form. In this way, some countries support other countries in their water needs. For water-scarce countries, it could be attractive to achieve water security by importing water-intensive products instead of producing all water-demanding products domestically. Reversibly, water-rich countries could profit from their abundance of water resources by producing water-intensive products for export. Trade of real water between water-rich and water-poor regions is generally impossible due to the large distances and associated costs, but trade in water-intensive products is realistic. (Hoekstra and Hung, 2002).

Considering virtual water in food as described by Renault (2003) as the amount of water per unit of food that is or would be consumed during its production process, the water requirements for food are by far the highest for example, it takes 2 to 4 liters per day to satisfy the biological needs (drinking water) of a human being and about 1,000 times as much to produce the food. For instance, a country that imports 1 million tons of wheat is importing and therefore enlarging its water resources by 1 billion m^3 of water. The VWF related to trade between nations could thus be used as an instrument to improve global water use efficiency and to achieve water security in water-poor regions of the world (Hoekstra and Hung, 2002) and is essential for developing a rational national policy with respect to virtual water trade (Hoekstra, 2003).

The VWF of trade has been calculated by multiplying international crop trade flows by their associated virtual water content. It depends on the specific water demands of the product in the exporting country.The VWF of trade is thus calculated as:

$$\mathrm{VWT}[n_e, n_i, c, t] = \mathrm{CT}[n_e, n_i, c, t] \times \mathrm{SWD}[n_e, c] \qquad \text{---------------} \ (2.17)$$

In which VWT denotes the VWF of product trade (in volume/time) from exporting country n_e to importing country n_i in year t as a result of trade in product c. CT represents the product trade (in mass/time) from exporting country n_e to importing country n_i in year t for product c. SWD represents the specific water demand (in volume/mass) of product c in the exporting country. The above equation assumes that if a certain product is exported from a certain country, this crop is actually grown in this country (and not in another country from which the crop was just imported for further export). Although certain errors will be made in this way, is estimated that these errors will not substantially influence the overall virtual water trade balance of a country. Besides, it is practically impossible to track the sources of all exported products (Hoekstra and Hung, 2002).

The gross virtual water import (GVWI) to a country n_i is the sum of all imports:

$$\mathrm{GVWI}[n_i, t] = \sum_{n_e, c} \mathrm{VWT}[n_e, n_i, c, t] \qquad \text{---------------} \ (2.18)$$

The gross virtual water export (GVWE) from a country n_e is the sum of all exports:

$$\mathrm{GVWE}[n_e, t] = \sum_{n_i, c} \mathrm{VWT}[n_e, n_i, c, t] \qquad \text{---------------} \ (2.19)$$

The net virtual water import of a country is equal to the gross virtual water import minus the gross virtual water export. The virtual water trade balance of country x for year t can thus be written as:

$$\mathrm{NVWI}[x,t] = \mathrm{GVWI}[x,t] - \mathrm{GVWE}[x,t] \qquad \text{--------------} \ (2.20)$$

In which NVWI stands for the net virtual water import (in volume/time) to the country. Net virtual water import to a country has either a positive or a negative sign. The latter indicates that there is net virtual water export from the country.

2.3 Cassava production

2.3.1 Cassava cultivation

Cassava (*Manihot esculenta* Crantz) belongs to the family Euphorbiaceae. It is a tropical root crop, originally from Amazonia that provides the staple food of an estimated 800 million people worldwide. The Amazonian Indians used cassava instead of or in addition to rice, potato or maize (Howeler *et al.*, 2013). Since 2000, the world's annual cassava production has increased by an estimated 100 million tones, driven in Asia by demand for dried cassava and starch for use in livestock feed and industrial applications. The major countries to produce cassava in the world are Nigeria, Brazil, Thailand, Indonesia and Congo, respectively.

Table 2.4 The major countries to produce cassava roots in the world: 2008-2012 (FAOSTAT, 2014a).

Countries	Productions (tons)	Area harvested (ha)	Yield (ton/ha)
World	248,976,986	19,850,320	12.5
Nigeria	46,068,177	3,595,204	12.8
Brazil	24,893,634	1,773,147	14.0
Thailand	24,214,879	1,235,240	19.6
Indonesia	23,147,463	1,172,871	19.7
Congo	15,221,164	1,985,978	7.7
Ghana	13,174,786	871,729	15.1
Angola	12,342,709	909,878	13.6
Viet Nam	9,215,891	533,757	17.3
India	8,712,260	246,040	35.4
Tanzania	5,193,143	897,286	5.8
Uganda	5,043,072	415,630	12.1
China, mainland	4,502,000	275,600	16.3

2.3.1.1 The environmental requirements of cassava cultivation

The details of the environmental requirements of cassava cultivation are as follows (DAFF, 2010);

1) Climatic requirements

Cassava is a typical tropical plant, for this reason, it is most productive between latitudes 15 °North and 15 °South. In general, the crop requires warm and humid conditions. The highest tuber production can be expected in the tropical lowlands below an altitude of 150 m where temperatures average between 25 °C and 29 °C.

Cassava produces best when rainfall is abundant, but it can be grown where the annual rainfall is as low as 500 mm but well distributed and where it is as high as 5,000 mm. The plant can stand prolonged periods of drought in which most other food crops would perish. This makes it valuable in regions where the annual rainfall is low or where seasonal distribution is irregular.

2) Soil requirement

Cassava grows best on light, sandy loams or on loamy sands, which are moist, fertile and deep, but it also grows well on soils ranging in texture from sands to clays and on soils of relatively low fertility. In practice, it is grown on a wide range of soils, provided the soil texture is friable enough to allow the development of the tubers.

3) Nutrient requirement

The application of fertilizers causes significant increases in yield of roots as well as starch content. Potassium salts favor the formation of starch, while nitrogen and phosphorus are essential for growth. Quantities of fertilizers required by a cassava crop depend on the nature of the soil. Soil analysis is therefore important to determine the quantity of fertilizer that has to be applied. Cassava requires large quantities of N, P, K fertilizers. Cassava production of 25 kg/ha requires about 60 kg/ha of N, 40 kg/ha of P_2O_5 and 136 kg/ha of K_2O.

4) Water requirement

Cassava does not have a critical period during which adequate soil moisture is essential for flowering and seed production. It also has several defense mechanisms that help it to conserve water, and its roots can grow to great depths to access subsoil moisture reserves. It can withstand relatively prolonged periods of drought. However, the crop is very sensitive to soil water deficit during the first three months after planting (FAO, 2013c). Cassava can grow in very dry areas such as northeast Brazil, southern India and Thailand. Research in Thailand found that maximum root yields were correlated with rainfall totaling about 1,700 mm/year during the 4th to 11th month after planting (Howeler and Tan, 2000). Cassava can be planted around April-May in the northern tropics and October-November in the southern tropics. During a survey in Thailand it was found that almost 50% of the cassava crop was planted between April to June as shown in Figure 2.10.

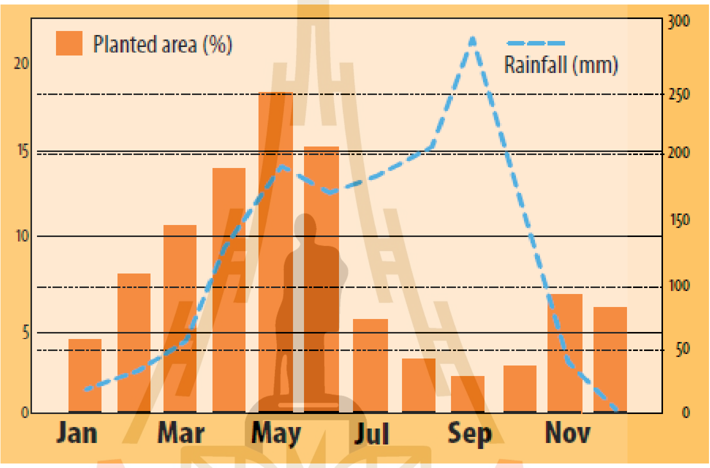


Figure 2.10 Rainfall and cassava planted areas at each month in Thailand.

Source: Howeler *et al*. (2013).

2.3.1.2 Cassava planted in Thailand

Cassava or tapioca plant is considered one of the most important economic crops in Thailand after rice and maize and it occupies the largest planted area. Major sources of cassava production are Nakhon Ratchasima, Chaiyaphum, Chachoengsao, Sa Kaeo, Kamphaeng Phet, Chon Buri and Kalasin provinces. This crop has excellent drought tolerance and can be planted with low input requirements and in almost all soil types where other crops cannot be cultivated economically. These features led to the rapid expansion of cassava planting throughout the country. Earlier, cassava was grown mainly in the Eastern and Central Plain of Thailand. However, cassava production area has shifted from the Central Plain to the Northeast, while the area of production in the North has also increased gradually (FAO, 2001). Cassava cultivation usually begins in April or May. The harvest season commences in March of the following year. Another, normally small, crop is planted in December after the end of the rainy season and it is harvested in November in the following year and the planting cycle is around 360 days. The productivity of cassava roots in Thailand has been significantly improved by almost 50% (from 15.63 tons/ha in 2001 to 22.93 tons/ha in 2007), which is attributable to the employment of improved varieties of cassava and good cultivation practices as a result of the collaboration of many government agencies and the private sector. Due to its excellent agronomic traits, improvements in root productivity and increased prices, cassava is now recognized as a cash crop that can generate more revenue for Thai farmers (Piyachomkwan and Tanticharoen, 2011).

The total cassava production in Thailand averaged 25 million tons per year. Of this, 27% was used for domestic consumption, divided by 8% and 19% in the form of pellets and starch, respectively. Of the total amount of cassava produced, 68% was for export in the form of pellets (32%) and starch (36%). Another, cassava is also composed of 5% as ethanol.

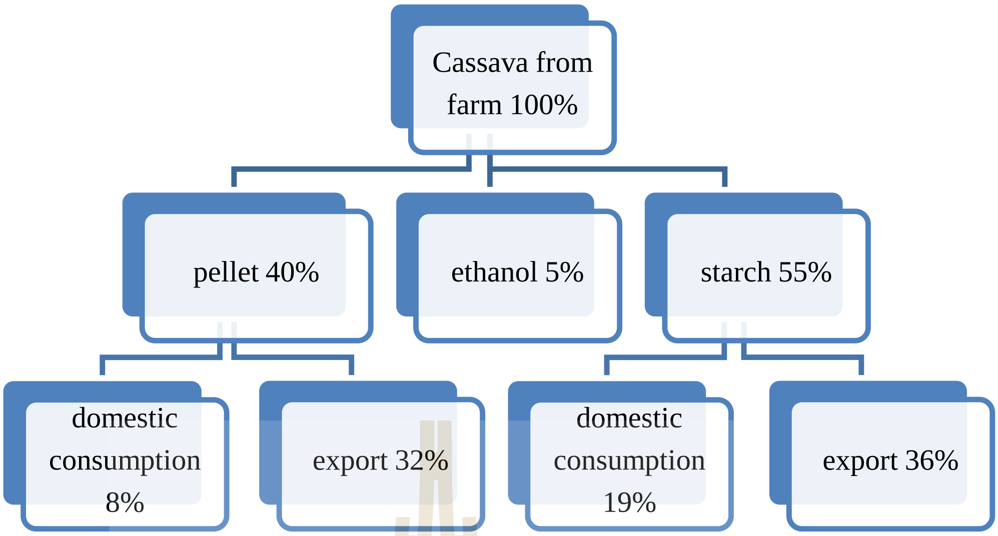


Figure 2.11 Flow of sources and use of cassava and its products in Thailand.

Source: Poramacom *et al.* (2013).

2.3.2 Cassava production and export market from Thailand

2.3.2.1 Cassava chips

Cassava chips are made from cassava that has been chopped into small pieces and sun-dried for 2-3 days. The chipping factories are installed with simple equipment, consisting mainly of a chopper. Roots are loaded into the hopper of the chopping machine by a tractor, after being chopped into small pieces, and the chips are sun-dried on a cement floor. The final moisture content of chips should be below 14% and the sand content should not exceed 3%. Normally it takes 2-2.5 kg of fresh roots (with 25% starch content) to produce 1 kg of chips (14% moisture content). Almost 90% of the cassava chips processed are exported. The remainder is used in various local industries such as the animal feed industry and for the production of ethanol.

2.3.2.2 Cassava pellets

The pellet industry began a few years after Thailand started exporting cassava chips to the EU. The development of this product was stimulated by the need to improve the uniformity in shape and size of cassava chips required by compound feed producers or users. After the removal of sand and other impurities, the dry chips are ground in a hammer mill. The cassava particles together with steam are forced through holes in the die. The compressed material emerges hot from the other side of the die and, after cooling, the strands are cut to length to produce pellets. The pellet diameter ranges from 5 to 6 mm and the length from 15 to 20 mm.

2.3.2.3 Cassava starch

The early stages of the development of the cassava starch industry in Thailand involved mostly cottage-scale factories. The process involved grating fresh roots, mixing with water, followed by sedimentation and sun-drying (or conductive heating), and the resultant product was traditionally named as ‘cassava meal’ or ‘cassava flour’. Demand for cassava starch increased dramatically and subsequently this led to the development of the modern starch manufacturing process in Thailand. Currently, there are about 79 modern starch factories, operating with mechanized processes for separation (e.g. dewatering centrifuge) and drying (e.g. flash dryer) with a total starch production of 15-17 million tons annually (production capacity of 23,500 tons starch/day). The processing time (from the grating of fresh roots to the drying of starch) is estimated to be less than 30 minutes. Around 40% of the starch produced is used domestically and the rest is for export markets in diversified forms including native, modified and hydrolyzed forms (e.g. sweeteners, sugar alcohols, amino acids, organic acids). Future exports of cassava starch are expected to increase due to the growth of the global industrial sector and starch markets (Piyachomkwan and Tanticharoen, 2011).

2.3.2.4 Export market of cassava production from Thailand

Cassava production is not only for domestic use but also for export, which annually produces more than 25 million tons of roots (Piyachomkwan and Tanticharoen, 2011). Thailand has become the world's largest exporter worldwide of cassava, consisting of dried cassava chips, pellets and flour. China, Korea and Japan still import dried cassava chips from Thailand, but for other purposes than feed, such as for ethanol fermentation. The dried cassava chip and pellet productions from Thailand generally export to the EU market (maximum of 5.25 million tons under the quota system), while the rest is exported to non-EU markets. On the other hand, Thailand export of cassava starch accounts for 85% of world exports, and it is exported to the five largest importers, namely, China, Indonesia, Taiwan, Malaysia and Japan. At present, the market structure of cassava production is well balanced with exports to ASEAN countries of 50%, 20% to the EU and the remainder is for domestic use. Cassava production for export from Thailand is shown in Table 2.5.

Table 2.5 Quantities of cassava production exported from Thailand (OAE, 2013b).

Year	Chip	Pellet	Starch	Total
	(tons)			
2000	34,015	3,212,896	1,048,230	4,295,141
2001	1,033,932	3,650,616	862,995	5,547,543
2002	1,369,033	1,534,998	849,410	3,753,441
2003	1,812,374	1,859,939	1,084,068	4,756,381
2004	2,805,988	2,212,948	1,113,434	6,132,370
2005	2,772,944	258,294	1,009,543	4,040,781
2006	3,930,294	393,315	1,669,660	5,993,269
2007	2,680,451	1,810,782	1,471,109	5,962,342
2008	1,202,463	1,646,730	1,272,169	4,121,362
2009	4,024,228	332,176	1,798,100	6,154,504

Table 2.5 (Continued).

Year	Chip	Pellet	Starch	Total
	(tons)			
2010	4,116,726	156,069	1,740,806	6,013,601
2011	3,693,514	36,694	1,891,343	5,621,551
2012	4,611,976	84,215	2,235,574	6,931,765
2013	5,755,376	59,082	2,445,612	8,260,070

It is proposed to rapidly increase the future export market of cassava starch production. As per the new agreement of the General Agreement on Trades and Tariffs (GATT), the Thai government has agreed to maximum market access of cassava starch and their modified products. Cassava has recently been considered as an energy crop that is being utilized for the production of bioethanol. Cassava based bioethanol production is a promising alternative to conventional fossil fuels and commercial production is already well established in Thailand. The research and development of cassava-bioethanol production technology is being implemented for the purpose of increasing crop productivity under the Thai government policy promotion. Hence, it is important that cassava crop output can currently satisfy the growing demand. The expansion of alternative energy production depends on the amounts of cassava supplied to bio-fuel production that uses material from the same land and resources as those used for food production. This will affect food production unless food and fuel production are integrated and produced from the same resources.

2.4 Sugar production

2.4.1 Sugarcane cultivation

The scientific name of sugarcane is *Saccharum officinarum* which belongs to the family Poaceae. Sugarcane is indigenous to tropical South and Southeast Asia and it originated in the South Pacific then appeared in the wild in East and North Africa, before moving through the Middle East, India, China, Taiwan, Malaysia and New Guinea (Sharpe, 2012). Sugarcane is currently the world's largest crop cultivated. FAO (2013). It is estimated that sugarcane is cultivated on about 26 million hectares in more than 90 countries, with a worldwide harvest of 1.83 billion tons. Brazil is the largest producer of sugarcane in the world and the next five major producers, in decreasing amounts of production are India, China, Thailand, Pakistan and Mexico. The major countries to produce sugarcane in the world are shown in the Table 2.6.

Table 2.6 The major countries to produce sugarcane in the world: 2008-2012 (FAOSTAT, 2014a).

Countries	Productions (tons)	Area harvested (ha)	Yield (ton/ha)
World	1,753,366,554	24,636,601	71.17
Brazil	701,890,694	9,028,211	77.74
India	325,787,560	4,735,918	68.79
China	117,684,721	1,728,538	68.08
Thailand	80,695,255	1,096,201	73.61
Pakistan	55,408,760	1,049,440	52.80
Mexico	50,337,358	710,984	70.80
Colombia	34,110,647	380,440	89.66
Philippines	31,300,000	405,974	77.10
Australia	29,100,204	364,713	79.79
USA	26,672,146	355,672	74.99
Indonesia	26,260,000	431,909	60.80
Argentina	25,968,000	353,000	73.56

2.4.1.1 The environmental requirements of sugarcane cultivation

The environmental requirements of sugarcane have been detailed as following (Netafim, 2013);

1) Climatic requirements

Temperature requirement: sugarcane is grown in the world from latitude 36.7 °North and 31.0 °South, from sea level to 1,000 m of altitude. It is considered a tropical plant. The optimum temperature for sprouting of stem cuttings is 32 to 38 °C and it slows down below 25 °C. Temperatures above 38 °C reduce the rate of photosynthesis and increase respiration. For ripening, relatively low temperatures in the range of 12-14 °C are desirable, since this has a noticeable influence on the reduction of vegetative growth rate and enrichment of sucrose in the cane.

Rainfall requirement: during the active growth period rainfall encourages rapid cane growth, cane elongation and internode formation. Nevertheless, during the ripening period high rainfall is not desirable because it leads to poor juice quality, encourages vegetative growth, formation of water shoots and increases in the tissue moisture.

Humidity requirement: high humidity (80-85%) favors rapid cane elongation during grand growth period. A moderate value of 45-65% coupled with limited water supply is favorable during the ripening phase.

2) Soil requirement

Soil is a medium for plant growth. It provides nutrients, water and encouragement to growing plants. Maintenance of proper physical, chemical and biological conditions of the soil is necessary for realizing higher growth, yield and quality of sugarcane. Sugarcane does not require any specific type of soil as it can be successfully raised on diverse soil types ranging from sandy soils to clay loams and heavy clays. It grows in soils with pH in the range of 5-8.5 and loamy soils with a bulk density of 1.1-1.2 g/cm^3 or 1.3-1.4 g/cm^3 in sandy soils.

3) Nutrient requirement

The nutrient requirements of sugarcane are relatively high, with 250-300 kg/ha of N, 80-100 kg/ha of P_2O_5 and 125-250 kg/ha of K_2O. The amounts of nutrients removed by sugarcane plants per ton of cane yield are as follows: 0.7-1.2 kg of N, 0.4-0.8 kg of P_2O_5 and 1.8-2.5 kg of K_2O.

4) Water requirement

Adequate available moisture throughout the growing period is important for obtaining maximum yields because vegetative growth including cane growth is directly proportional to the water transpired. Sugarcane is a long duration crop producing huge amounts of biomass and is classed among those plants having a high water requirement and yet it is drought tolerant. The plant crop season is 12-18 months in India, 13-14 months in Iran, 16 months in Mauritius, 13-19 months in Jamaica, 15 months in Australia and 20-24 months in Hawaii.

The seasonal crop water requirements for sugarcane in Thailand are estimated at between 1,100-1,500 mm/year under a range of climatic conditions and varying lengths of growing seasons (10-14 months), with a daily evapotranspiration rate of 4-7 mm/day. The water requirements of sugarcane in Thailand depend on the climate and early growth stages, and they can be divided into four phases as shown in Table 2.7.

Table 2.7 Water requirements of sugarcane in different growing stages of Thailand.

Period growing stage	Water requirement	
	mm/day	mm/stage
Initial stage(30 days)	4	120
Development stage (140 days)	4.5	630
Middle stage (125 days)	5	625
End of stage (35 days)	4	140
Total	**-**	**1,515**

Source: http://oldweb.ocsb.go.th/udon/All%20text/1.Article/01-Article%20P8.2.htm.

2.4.1.2 Sugarcane planting in Thailand

In recent years growth in sugarcane production has come largely from expansion in the North and Northeast regions. More than 95% of the sugarcane is cultivated in rain-fed areas. Major sources of sugarcane plantation in Thailand are Nakhon Ratchasima, Kanchanaburi, Nakhon Sawan, Khonkaen and Suphan Buri provinces. The recent success of the industry can be attributed to several key factors, including attractive sugarcane prices, sugar factory relocation and capacity expansion policies, which have successfully encouraged the extension of sugarcane areas. The third factor is favorable weather. Since less than 10% of sugarcane area, now over one-million ha, is irrigated, favorable rainfall distribution has been an important factor in improved yields. Sugarcane crop plantation varies in months by region, but generally it is planted in May to June, and the growing period is about 10 to 14 months depending on the variety of the cane. Farmers generally grow only one or two ratoon crops, and as a result, they can change the areas planted relatively quickly in response to world price changes. Yields of sugarcane have been gradually improving with the greater use of fertilizers and pesticides and improved cane varieties. Expansion of irrigation is especially important as more land is put into cane production in the drought-prone Northeast-region (FAO, 1997).

2.4.2 Production, consumption and export market of sugar from Thailand

2.4.2.1 Sugarcane production

Sugarcane production increased formerly to 10-11 million tons and is now up to 100 million tons in current production, due to an increase in planting areas and the construction of new sugar mill facilities. However, it decreased to 99.5 million tons in 2012/13 due to lower-than-expected sugarcane extraction rates caused by drought. This slowed sugar exports, which had doubled in the previous year. Meanwhile, in 2013/14 sugar production recovered to approximately 10.5 million tons in anticipation of a larger sugarcane crop and the improvement in sugarcane extraction rates due to favorable weather conditions. The number of sugar mills are expected to increase to 51 mills with a total production capacity of approximately 1.0 million tons/day, up from 47 mills with a production capacity of 0.9 million tons/day in the past three decades (USAD, 2012). Sugarcane production is forecast to increase continuously. Most of the sugarcane harvest will be primarily used for sugar production, with a minimal use for gasohol production, although gasohol consumption has increased in Thailand. The gasohol accounts for approximately 0.6 percent of sugarcane production. At present, there are sugarcane based ethanol plants operating in Thailand which produce about 30 to 40 million liters of ethanol/year using 0.4 to 0.5 million tons of cane/year (USAD, 2013).

2.4.2.2 Consumption

Thailand's sugar consumption is part of industrial and domestic uses and it increased to approximately 2.5 million tons in 2011/2012, up around 5% from the previous year, and upward to 2.8 million tons in 2012/13 as in anticipation of a domestic economic recovery (USAD, 2013). In industrial use, which accounts for 40% of total sugar consumption, sugar consumption in the beverage industry accounts for approximately half of the total industrial use. Domestic sugar consumption accounts for around 60% of total sugar consumption. Therefore, according to a report of the Ministry of Public Health, per capita consumption of sugar has tripled from the standard of 10.0 kg/year to around 30.0 kg/year over the past five years. Meanwhile, domestic use is expected to increase by around 7.0%, and up to 1.4-1.5 million tons/year (USAD, 2012).

2.4.2.3 Export market of sugar production from Thailand

Sugar is one of the largest traded commodities in the world. Thailand is one of the world's leading sugar exporting countries, and it is nowfirmly the second-biggest exporter. At present, two thirds of all exported sugar in the world is raw sugar, while one third is refined sugar. Brazil remains dominant in the raw sugar market. Furthermore, the top five exporters of raw sugar, which are Brazil, Thailand, Guatemala, India and Cuba, supply 85% of the total exported volume. The Middle East and Asia account for about 70% of the imports of the world's raw sugar. In addition, in the refined sugar market, Brazil, Thailand, Mexico and the EU export over 60% of all refined sugar. Thailand's exports can be divided into three major groups: raw sugar, refined sugar and molasses. In 2011/12, Thailand's exports increased to 7.9 million tons of raw value, up to 19 percent from the previous year due to acreage expansion. The increase was reflected in a surge of raw sugar exports, particularly to Japan, South Korea, Malaysia, Russia, Indonesia and China, due to limited exportable supplies from Australia and Brazil caused by unfavorable weather conditions (USAD, 2012). Most of the raw sugar exported to Indonesia accounted for approximately 30% of the total amount of raw sugar. Refined sugar was mostly exported to Cambodia, which accounted for approximately 17% of the total refined sugar. Exports of molasses decreased continually in demand in 2006 to 2013 down to approximately 50% of the the previous demand because the Thai government currently promotes the production of the alternative fuel of ethanol, which has resulted in the ethanol industry continuing to grow steadily. The export of sugar production and molasses is shown in Table 2.8.

Table 2.8 Quantities of sugar production and molasses exported from Thailand (OAE, 2013b).

Year	Raw sugar	Refined sugar	Molasses	Total
		(tons)		
2000	2,316,211	1,771,223	1,009,546	5,096,980
2001	2,207,154	1,038,624	1,412,981	4,658,759
2002	2,054,106	1,974,841	1,358,075	5,387,022
2003	2,543,522	2,521,307	1,328,178	6,393,007
2004	2,234,201	2,352,673	1,499,504	6,086,378
2005	1,557,497	1,454,621	1,159,491	4,171,609
2006	1,264,382	1,008,751	502,095	2,775,228
2007	2,080,618	2,345,458	549,336	4,975,412
2008	2,972,968	2,038,855	786,953	5,798,776
2009	2,342,897	2,709,673	443,770	5,496,340
2010	2,068,893	2,431,826	237,319	4,738,038
2011	4,116,824	2,404,221	396,943	6,917,988
2012	4,244,132	2,606,158	979,637	7,829,927
2013	3,128,252	2,866,694	544,803	6,539,749

In future, sugarcane production is forecast to increase in plantation because sugarcane is considered as an energy crop that is being utilized for the production of bioethanol. Moreover, increased demand for sugar would most likely come from industrial users for the manufacture of processed foods and beverages. Hence, the Thai government and the Office of Cane and Sugar Board (OCSB), have joined hands to increase the sugarcane yield. Their purpose is to invest more to achieve a higher yield production of four to five times higher than normal which provides Thai farmers with yields of over 100 ton/ha. A pivotal factor in achieving the production goals of the industry is the improvement of sugar yield per ton of cane. Sugar yield depends on several factors relative to sugarcane production (harvesting and handling conditions and quality) and the sugar factories (process, operations and composition of output). This includes turning demonstration sites into real plantations and increasing financial support for farmers, as the process requires much investment of capital. However, the Thai government also supports environmental protection by means of a breakout year with green policies and projects to develop Thailand into a low-carbon society. In addition, social and environmental sustainability has led to the investigation of land and water use in other aspects related to the cultivation of food and energy crops and their production.

CHAPTER III

RESEARCH METHODOLOGY

This chapter describes the research work that consists of 1) setting the goals and scope of this study, 2) the methodology to calculate the WF of crop cultivation, crop production and VWF of their trade, 3) the data resources for calculation and analysis, and 4) the CROPWAT 8.0 program software work, all of which are presented as follows:

3.1 Setting the goals and scope of this study

This is an applied research study that has been proposed to assess WF and VWF of commodity trade specifically for cassava starch and refined sugar of Thailand during the period of 2008-2013. This study is divided into three sections:

1) To estimate the appropriate amount of water needed to produce cassava and sugarcane crops. The WF of crop cultivation is comprised of green, blue and grey components, which are presented in terms of cubic meters per ton of crop. The study area of cassava cultivation was 45 provinces of which 13, 19 and 13 provinces were in the Northern, Northeastern and Central Plain of Thailand, respectively. In addition, the area of sugarcane cultivation was studied in 47 provinces that were in 12, 18 and 17 provinces in the Northern, Northeastern and Central Plain of Thailand, respectively.

2) Determination of the water volume that is embedded in the products is defined in terms of cubic meters per ton of crop products which results from cassava root or sugarcane production are transformed to a final product of cassava starch or

refined sugar. Three cassava starch and one refined sugar factory within Nakhon Ratchasima province were selected for the collection of water consumption data that was applied to calculate the WF of products. In addition, the secondary data was selected from previous studies in Thailand concerning the water consumption recorded in the form of the Life Cycle Inventory (LCI) data which is associated with cassava starch and refined sugar processing. Thus, the results of the average WF of products in Thailand were calculated based on the primary and secondary data.

3) To calculate the net VWF of trade cassava starch and refined sugar which is related to the differences between their exports and imports worldwide. The function unit of water volume of VWF is defined as a cubic meters per year. The overall calculation of steps on WF and VWF of trade is shown in Figure 3.1.

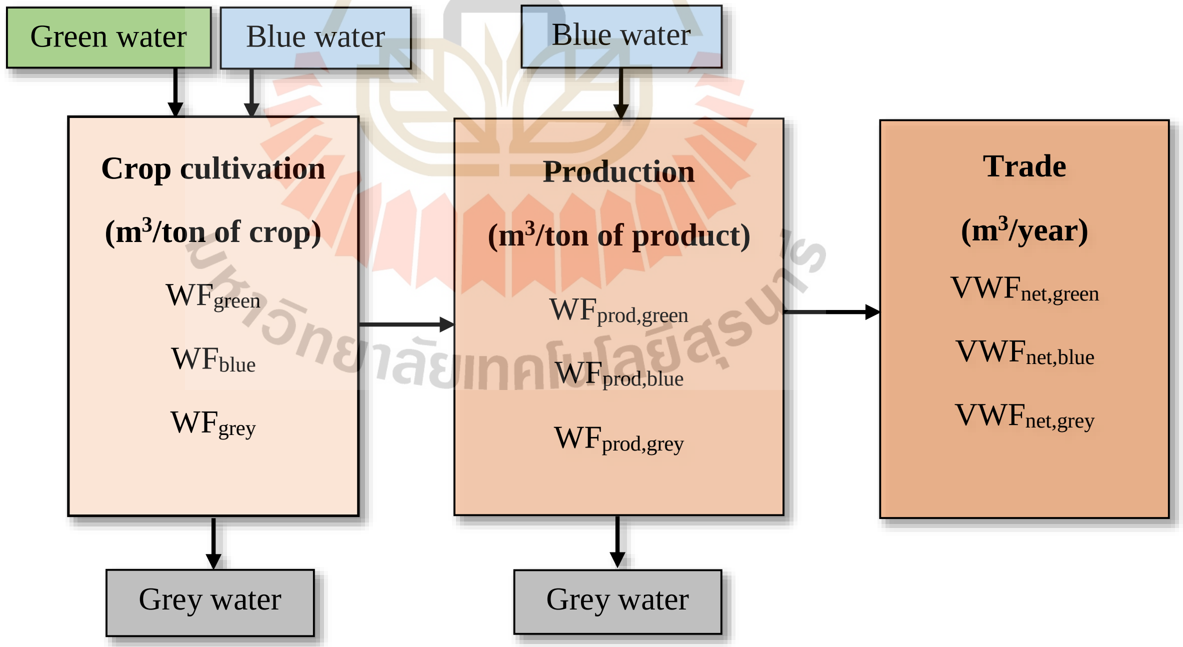


Figure 3.1 Overall calculation of steps on water footprint and virtual water flow of trade.

3.2 Methods

3.2.1 Calculation of water footprint of crop cultivation

The Water Footprint Assessment Manual by Hoekstra *et al.* (2011) was used to assess the green and blue WFs of cassava and sugarcane cultivation in Thailand. The WF was estimated under both the crop water requirement (CWR)-option and the irrigation schedule-option by using the CROPWAT 8.0 program, which was developed by FAO, and which is based on the assumptions of Allen *et al*. (1998). The grey WF is also estimated by use of The Water Footprint Assessment Manual by Hoekstra *et al.* (2011) and the Grey Water Footprint Accounting by Franke *et al.* (2013), and the WF of the crops cultivation was calculated following the steps given below:

3.2.1.1 Green and blue water footprints of crop cultivation

1) Calculation of crop water requirement (CWR)

The CWR is calculated from the accumulated crop evapotranspiration (ET) over the complete growing period by using the CROPWAT 8.0 program. ET_c estimated under the CWR-option is equal to the CWR. On the other hand, ET_a estimated under the irrigation schedule-option. Hoekstra *et al.* (2011) described the ET_c calculation indirectly as requiring climatic data, effective rainfall and crop characteristics, whereas the ET_a required the same parameters as ET_c but with the addition of the soil data.

The ET_c is calculated by multiplying the reference crop evapotranspiration; ET_o estimated on standard conditions over the growing season with the crop coefficient; K_c, it is calculated as follows:

$$ET_c = K_c \times ET_o \quad \text{---------------- (3.1)}$$

The ET_a was estimated on standard or non-standard conditions over the growing season, using the daily soil water balance approach calculated as follows:

$$ET_a = K_c \times K_s \times ET_o \qquad \text{---------------- (3.2)}$$

Where K_s is the stress coefficient that describes the effect of water stress on crop transpiration. This factor is dependent on the available soil water with a value between zero and one (Mekonnen and Hoekstra, 2010). With regard to the soil water limiting conditions; $K_s < 1$, while there is no soil water stress; $K_s = 1$ (Allen *et al.*, 1998).

The ET_o was introduced by the FAO, which expresses the evapotranspiration from a hypothetical grass reference crop that is not short of water. The only factors which effect ET_o are climatic parameters and the crop characteristics and soil data are not considered. The ET_o is calculated on the basis of the FAO Penman-Monteith equation as follows (Smith *et al.*, 1992; Allen *et al.*, 1994; Allen *et al.*, 1998; Hoekstra and Hung, 2002):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.3U_2)} \qquad \text{--------------- (3.3)}$$

Where:

ET_o = reference crop evapotranspiration (mm/day)

R_n = net radiation at the crop surface (MJ/m^2-day)

G = soil heat flux (MJ/m^2-day)

T = average air temperature (°C)

U_2 = wind speed measured at 2 m height (m/s)

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

e_s-e_a = vapor pressure deficit (kPa)

Δ = slope of the vapor pressure curve (kPa /°C)

γ = psychrometric constant (kPa/°C)

In other words, the green evapotranspiration; ET_{green} can be equated with the minimum of total ET_c and with the effective rainfall; P_{eff}. The Blue evapotranspiration; ET_{blue} field-evapotranspiration of irrigation water, is equal to the ET_c minus P_{eff}, but is zero when P_{eff} exceeds crop evapotranspiration. The ET_{green} and ET_{blue} are equal as in the following equation:

$$ET_{green} = \min(ET_c, P_{eff}) \quad \text{---------------} \ (3.4)$$

$$ET_{blue} = \max(0, ET_c - P_{eff}) \quad \text{---------------} \ (3.5)$$

2) Calculation of crop water use (CWU)

The green or blue component in CWU; CWU_{green} or CWU_{blue} (in m^3/ha) are calculated by the accumulation of daily ET (in mm/day) over the complete growing period, which can be expressed by the following equation:

$$CWU_{green} = 10 \sum_{d=1}^{lgp} ET_{green} \quad \text{----------------} \ (3.6)$$

$$CWU_{blue} = 10 \sum_{d=1}^{lgp} ET_{blue} \quad \text{----------------} \ (3.7)$$

Where the factor 10 is applied to convert the unit from mm into m^3/ha. The lgp denotes the length of the growing period in days.

The green and blue components are the volumes of water evaporated for crop production. Hence, the CWU is illustrated by evapotranspiration and $\mathrm{CWU}_{\mathrm{eva}}$ is the equal summation of the green and blue components:

$$\mathrm{CWU}_{\mathrm{eva}} = \mathrm{CWU}_{\mathrm{green}} + \mathrm{CWU}_{\mathrm{blue}} \qquad \text{---------------} \tag{3.8}$$

3) Calculation of water footprint (WF)

Calculation of the green or blue WF; $\mathrm{WF}_{\mathrm{green}}$ or $\mathrm{WF}_{\mathrm{blue}}$ (in m^3/ton) is calculated as the $\mathrm{CWU}_{\mathrm{green}}$ or $\mathrm{CWU}_{\mathrm{blue}}$ (in m^3/ha) divided by the crop yield; Y (in ton/ha):

$$\mathrm{WF}_{\mathrm{green}} = \frac{\mathrm{CWU}_{\mathrm{green}}}{\mathrm{Y}} \qquad \text{---------------} \tag{3.9}$$

$$\mathrm{WF}_{\mathrm{blue}} = \frac{\mathrm{CWU}_{\mathrm{blue}}}{\mathrm{Y}} \qquad \text{---------------} \tag{3.10}$$

3.2.1.2 Grey water footprint of corps cultivation

The grey WF; $\mathrm{WF}_{\mathrm{grey}}$ (in m^3/ton) of growing a crop, is calculated by multiplying the chemical application rate; AR per hectare (in kg/ha) with the leaching-run-off fraction; α (in percent of AR) divided by the difference between the ambient water quality standard for that pollutant [the maximum allowable concentration; C_{max} (in kg/m^3) and its natural background concentration in the receiving water body; C_{nat} (in kg/m^3)], and then divided by the crop yield: Y (in ton/ha), in the following equation:

$$\mathrm{WF}_{\mathrm{Grey}} = \frac{(\mathrm{AR} \times \alpha)/(C_{\mathrm{max}} - C_{\mathrm{nat}})}{\mathrm{Y}} \qquad \text{---------------} \tag{3.11}$$

In this study, it is assumed that the leaching-run-off fraction (α) is equal to 10% of the applied N-fertilizer per hectare that is lost through leaching (Chapagain *et al.*, 2006; Mekonnen and Hoekstra, 2010; Frank *et al.*, 2013). The recommended maximum value of nitrate in surface and groundwater used in this study was selected by C_{max} by the Thai ambient water quality standard, as recommended by the Office of Natural Resources and Environmental Policy and Planning (ONPE, 2013) which is 5 mg/L of nitrate-nitrogen, because nitrogen is used as a nonpoint source that affects rivers. Regarding C_{nat}, there is a lack of appropriate data about the natural concentration in the receiving water bodies from local information so it is quite difficult to estimate. It was assumed to be zero for the purposes of this study (Mekonnen and Hoekstra, 2010).

3.2.1.3 Total water footprint of crop cultivation

The total WF; WF_{total} (in m^3/ton) of crop cultivation is the sum of the green, blue and grey components as in the following:

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \qquad \text{--------------} \ (3.12)$$

In this study, the volumes of water use that implicated in the term evapotranspiration are called 'WF_{eva}' and non-evapotranspiration is called '$WF_{non\text{-}eva}$', as the WF concerned with evapotranspiration was the WF within the green and blue components, but the WF concerned in non-evapotranspiration was the grey component. Hence, the total WF in this study is expressed as in the following equation:

$$WF_{total} = WF_{eva} + WF_{non\text{-}eva} \qquad \text{---------------} \ (3.13)$$

Where WF_{eva} is the volume of water evaporated, $WF_{non\text{-}eva}$ is the volume of water unavailable for the results of water pollution.

$$WF_{eva} = WF_{green} + WF_{blue} \qquad \text{---------------} \ (3.14)$$

$$WF_{non\text{-}eva} = WF_{grey} \qquad \text{---------------} \ (3.15)$$

The overall scheme for the calculation of WF of crop cultivation is expressed in Figure 3.2.

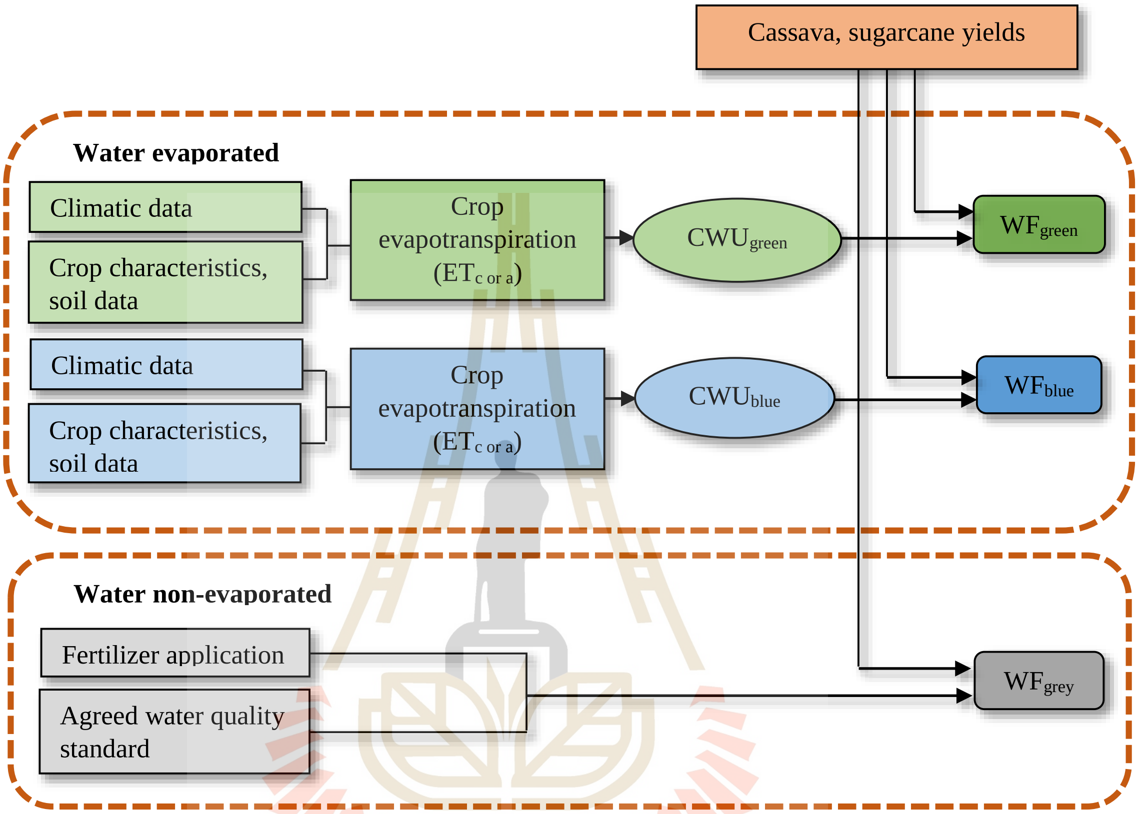


Figure 3.2 Diagram to assess the water footprint of crop cultivation.

3.2.2 Calculation of water footprint of product

The stepwise accumulative approach is the best way to calculate the amount of water consumption and wastewater generated throughout the process. The water mass flow balance per one ton of product obtained from the primary data at site factories must be used to calculate the WF of the product. However, using the amount of water consumption and wastewater data obtained from secondary data at previous studies made in Thailand (from the literature review) to calculated the WF of product. The WF of cassava starch and refined sugar in Thailand is averaged out with primary and secondary data which calculated based on the amount of water use and wastewater generation from cassava starch and refined sugar processing.

To assess the WF of the product in this study, the amount of water use was calculated from the crop cultivation and transformed into the production processing (in m^3/ton of product), and classified into green, blue and grey components. The WF of the product is calculated as follows:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]} \right) \times f_v[p] \quad \text{--------------} \ (3.16)$$

Where $WF_{prod}[p]$ is the WF (in m^3/ton) of the output product p, $WF_{prod}[i]$ is the WF of the input product i and $WF_{proc}[p]$ is the process WF (in m^3/ton) of the processing step that transforms the y input products into the z output products, expressed in water use per unit of processed product p. The $f_p[p,i]$ is a product fraction (in ton/ton) that is defined as the quantity of the output product per quantity of input product, and $f_v[p]$ is a value fraction (in monetary unit/monetary unit) which is defined as the ratio of the market value of this product to the aggregated market value of all the output products (p=1 to z) obtained from the input products.

3.2.3 Calculation of virtual water flow of trade

The VWF of trade between nations has been calculated by multiplying the international products trade flow with their associated WF of the product. In this study, the VWF of trade concerned the export and import of cassava starch and refined sugar of Thailand between the years 2008-2013.

The VWF of export; VWF_{exp} (in m^3/year) in a country was thus obtained by multiplying the quantities of commodity trade that were exported; CT_{exp} (in ton/year) by the WF of its products; WF_{prod} (in m^3/ton) as follows:

$$\mathrm{VWF_{Exp}} = \mathrm{CT_{exp}} \times \mathrm{WF_{prod}} \qquad \text{---------------} \ (3.17)$$

Also, the VWF of imports; VWF_{imp} (in m^3/year) in a country was obtained by multiplying the quantities of commodity trade that were imported; CT_{imp} (in ton/year) by the WF of its products; WF_{prod} (in m^3/ton) as follows:

$$\mathrm{VWF_{imp}} = \mathrm{CT_{imp}} \times \mathrm{WF_{prod}} \qquad \text{---------------} \ (3.18)$$

The net VWF of trade; VWF_{net} (in m^3/year) can be estimated from the difference between the VWF of export; VWF_{exp} (in m^3/year) and the VWF of imports; VWF_{imp} (in m^3/year). The equation is as follows:

$$\mathrm{VWF_{net}} = \mathrm{VWF_{exp}} - \mathrm{VWF_{imp}} \qquad \text{--------------} \ (3.19)$$

The overall projection can be seen in the assessment steps of WF and VWF of trade cassava starch and refined sugar as illustrated in Figure 3.3.

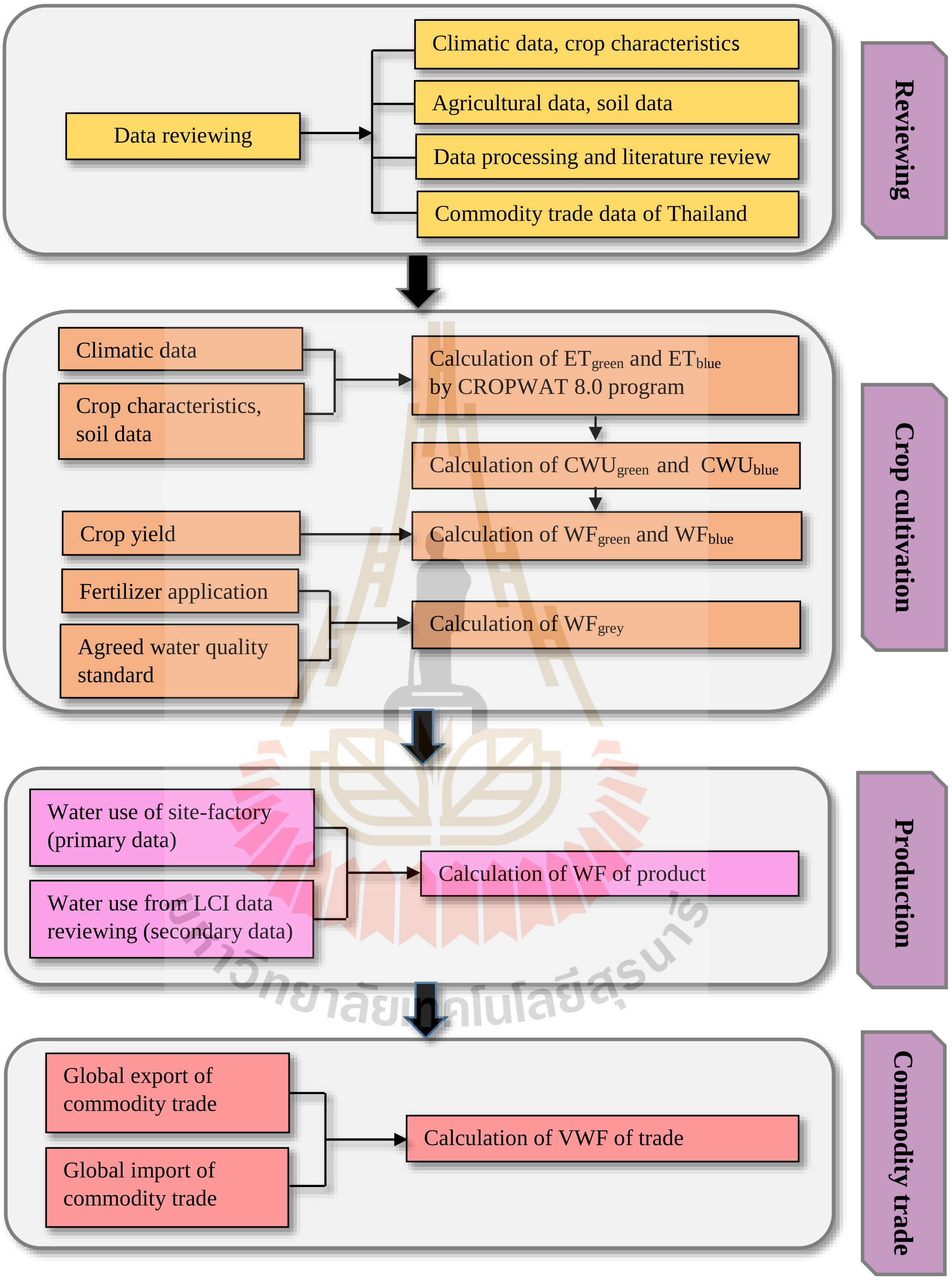


Figure 3.3 Diagram for assessment steps of water footprint and virtual water flow of trade cassava starch and refined sugar.

3.3 Data sources

This study focused on assessing the WF and VWF of trade cassava starch and refined sugar of Thailand during 2008-2013. Data were obtained from the secondary data in different sources which were applied to calculate the WF and VWF of trade and which obtained the following results;

3.3.1 Data for calculating the water footprint of crop cultivation

3.3.1.1 Geographical data

The geographical data representative of the crop location were input to the CROPWAT 8.0 program. In this study, the geographical data were collected from selected meteorological stations in those provinces that provide data about latitude, longitude and altitude. These data are specified in Appendix A.

3.3.1.2 Climatic data

The climatic data was needed as input to the CROPWAT 8.0 program to calculate the ET_o. The climatic data provided by the Thai Meteorological Department (TMD) were available at different meteorological stations located in different provinces. For some provinces where the data were not available, the data have been taken from the nearest meteorological station in another province. In the case of provinces with a very large area, which generally have two or more meteorological stations, the main meteorological station was selected to obtain the data. The average data of the climatic parameters during 2008-2013 included maximum temperature (°C), minimum temperature (°C), humidity (%), sunshine hours (hours), wind speed (km/day) and total rainfall (mm/month) as specified in Appendix B.

3.3.1.3 Crop characteristics

The crop characteristics directly inserted into the CROPWAT 8.0 program to calculate the ET were available on the website published by the Natural Resources Management and Environment Department of FAO. The crop characteristics were comprised of K_c during different crop development stages (initial, middle and late stage), the length (in days) of crop in each development stage, the root depth (m), critical depletion (%) and crop height (m), as provided by Allen *et al.* (1998). The yield response factor (K_y), which was obtained from the Land and Water Division of FAO was provided by Steduto *et al*. (2012).

3.3.1.4 Soil data

Soil data were essential input required for the CROPWAT 8.0 program to estimate the ET. Soil series and soil types are quite specific according to the type of crop grown that are defined by the Land Development Department (LDD). Furthermore, to determine the initial available soil moisture data was required for input including the total available soil moisture, maximum rain infiltration rate, maximum rooting depth and initial soil moisture depletion, as specified in Appendix C.

3.3.1.5 Agricultural data

The pooled data from the period of 2008-2013 including harvested area (in ha), production (in ton/year) and crop yield (in ton/ha) of cassava and sugarcane cultivation were obtained from the Office of Agricultural Economics (OAE). This included the fertilizer application rate applied to the crop field as directed by the Department of Agriculture (DOA).

3.3.2 Data to calculate water footprint of production

The amount of water used in processing was established by the water mass flow balance based on one ton of product. The data collected from three cassava starch factories and one refined sugar factory are located in Nakhon Ratchasima province. Moreover, the data selected for the amount of water use from LCI data of cassava starch and refined sugar was obtained from the literature review of previous Thai studies.

3.3.3 Data for calculating the virtual water flow of trade

Data sources required for calculating the VWF of trade cassava starch and refined sugar of Thailand were classified according to the annual export and import of the average of these products during the period 2008-2013. These data were obtained from the Office of Agricultural Economics, Thailand (OAE).

The important parameters and their data sources required for assessing WF and VWF of trade are given in Table 3.1.

Table 3.1 Parameters and data sources for the water footprint calculation.

Parameters	Data sources
1. WF of crops cultivation	
- Climatic data	Thai Meteorological Department; TMD
- Crop characteristics	
• Crop characteristics	FAO, provided by Allen *et al*. (1998)
• Yield response factor	FAO, provided by Steduto *et al*. (2012)
- Soil data	
• Soil series and soil types	Land Development Department; LDD
• Total available soil moisture	Nilpunt (2013)
• Maximum rain infiltration rate	Israelsen *et al*. (1980)
• Maximum rooting depth	Hoondee (2005)
• Initial soil moisture depletion	FAO (2013b), Hoondee (2005)

Table 3.1 (Continued).

Parameters	Data sources
- Agricultural data	
• Harvested areas, crop production and crop yield	Office of Agricultural Economics; OAE
• Fertilizer applications	Department of Agriculture; DOA
2. WF of products	
- LCI data (primary data)	factories in Nakhon Ratchasima province
- LCI data (secondary data)	Literatures review
3. VWF of trade	
- Annual export and import of commodity trade	Office of Agricultural Economics; OAE

3.4 CROPWAT 8.0 program

The CROPWAT version 8.0 is a computer program used for irrigation planning and management that has been developed by the Land and Water Development Division of FAO (Smith *et al.*, 2002) and it can be downloaded through the FAO website, (FAO, 2013a). The user guidelines and the examples given show how to use the CROPWAT 8.0 program which are also available on the FAO website, (FAO, 2013b). This program provides many functions to calculate ET_o, CWR and scheme irrigation, based on climate, crop characteristics and soil data input. In addition, the program calculates the ET_o based on the FAO Penman-Monteith method. The CWR and scheme irrigation require a quantity of effective rainfall that is calculated by using the Soil Conservation Service (SCS) method, developed by United States Department of Agriculture (USDA). The CROPWAT 8.0 program was designed to improve irrigation practices and provide the planning of irrigation schedules in different conditions that estimate the water supply for various crops. All calculation procedures used in CROPWAT 8.0 are based on the two FAO publications of the Irrigation and

Drainage Series, namely, No. 56 ‘Crop Evapotranspiration- Guidelines for computing crop water requirements’ written by Allen *et al.* (1998) and No. 33 ‘Yield response to water’ written by Doorenbos *et al.* (1979). All these procedures are available on the FAO website.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Water footprint of cassava and sugarcane cultivation

4.1.1 Agricultural data

4.1.1.1 Cassava and sugarcane cultivation

Cassava and sugarcane are generally grown in Northern, Northeastern and the Central Plain of Thailand. The government determines the strategy to promote high productivity. The OAE revealed data such as harvested area, production and crop yield, as shown in Table 4.1.

Table 4.1 Average of harvested area, production and yield of cassava and sugarcane cultivation in various provinces of Thailand (OAE, 2010 and 2013a).

Provinces	Cassava			Sugarcane		
	Harvested area (ha)	Production (ton/year)	Yield (ton/ha)	Harvested area (ha)	Production (ton/year)	Yield (ton/ha)
Northern						
Chiang Rai	3,117	61,087	19.60	-	-	-
Phayao	831	16,921	20.36	-	-	-
Lampang	1,116	22,158	19.85	5,003	246,075	49.19
Chiang Mai	-	-	-	411	23,268	56.61
Tak	7,884	181,950	23.08	1,435	87,636	61.07
Kampaeng Phet	86,159	1,887,862	21.91	67,000	5,385,011	80.37
Sukhothai	3,506	67,210	19.17	26,967	1,921,680	71.26
Phrae	720	14,187	19.70	331	22,408	67.70
Uttaradit	3,207	65,763	20.51	14,829	1,061,496	71.58
Phitsanulok	27,833	594,975	21.38	21,328	1,526,503	71.57
Phichit	1,205	25,212	20.92	7,731	540,858	69.96
Nakhon Sawan	46,505	982,626	21.13	91,842	7,508,447	81.75
Uthai Thani	28,509	596,867	20.94	38,004	2,916,454	76.74
Phetchabun	16,339	357,905	21.90	42,177	3,502,630	83.05
Total	226,931	4,874,723	21.48	317,058	24,742,466	70.04

Table 4.1 (Continued).

Provinces	Cassava			Sugarcane		
	Harvested area (ha)	Production (ton/year)	Yield (ton/ha)	Harvested area (ha)	Production (ton/year)	Yield (ton/ha)
Northeastern						
Loei	33,019	686,446	20.79	13,452	899,705	67.76
Nong Bua Lam Phu	6,923	140,150	20.24	10,910	740,374	66.96
Udon Thani	32,011	649,393	20.29	58,866	3,935,487	69.06
Nong Khai	6,290	123,374	19.61	1,122	76,031	71.18
Sakhon Nakhon	14,865	279,028	18.77	4,193	280,764	70.41
Nakhon Phanom	4,895	94,040	19.21	976	67,405	70.29
Mukdahan	17,703	345,325	19.51	15,505	1,103,611	67.76
Yasothon	10,166	209,596	20.62	1,984	139,689	66.96
Amnat charoen	6,354	130,439	20.53	1,450	101,924	69.06
Ubon Ratchathani	30,788	612,733	19.90	-	-	-
Si Sa Ket	14,047	292,339	20.81	867	58,169	67.09
Surin	9,553	194,061	20.31	26,162	1,775,862	67.88
Buri Ram	32,889	703,862	21.40	19,768	1,399,398	70.79
Maha Sarakham	16,394	322,161	19.65	10,274	688,854	67.05
Roi Et	10,986	222,135	20.22	5,561	403,074	72.48
Kalasin	41,414	873,170	21.08	43,686	3,173,783	72.65
KhonKaen	34,577	673,875	19.49	79,472	6,023,731	75.80
Chaiyaphum	60,662	1,217,131	20.06	57,238	4,022,052	70.27
Nakhon Ratchasima	287,606	5,807,164	20.19	91,115	6,241,218	68.50
Total	671,142	13,576,422	20.23	442,601	31,131,131	70.34
Central Plain						
Saraburi	4,955	99,347	20.05	24,294	1,719,873	70.79
Lop Buri	26,650	542,882	20.37	52,977	3,754,052	70.86
Sing Buri	-	-	-	7,279	547,835	75.26
Chai Nat	11,466	216,375	18.87	8,579	657,387	76.63
Suphan Buri	5,852	113,795	19.45	68,079	5,651,124	83.01
Ang Thong	-	-	-	2,604	191,096	73.39
Prachin Buri	26,008	547,169	21.04	1,402	90,624	64.64
Chachoengsao	45,932	986,861	21.49	6,888	424,206	61.59
Sa Kaeo	59,892	1,218,292	20.34	32,837	2,103,653	64.06
Chantaburi	38,847	806,986	20.77	2,691	168,940	62.78
Rayong	22,461	484,532	21.57	3,728	235,607	63.20
Chon Buri	46,252	1,066,571	23.06	16,795	1,082,662	64.46
Nakhon Prathom	-	-	-	12,276	955,948	77.87
Kanchanaburi	55,645	1,114,306	20.03	105,249	7,767,291	73.80
Ratchaburi	13,107	262,091	20.00	28,904	2,009,132	69.51
Phetchaburi	401	8,386	20.91	3,907	247,408	63.32
Prachuap Kiri Khan	-	-	-	5,277	328,214	62.20
Total	357,468	7,467,593	20.89	383,766	27,935,052	72.79

Data from Table 4.1 can be summarized by region as follows:

1) Northern region

Cassava is cultivated in 13 provinces that include Chiang Rai, Phayao, Lampang, Tak, Kampaeng Phet, Sukhothai, Phrae, Uttaradit, Phitsanulok, Phichit, Nakhon Sawan, Uthai Thani and Phetchabun provinces. The total harvested area and production were 226,931 ha and 4,874,723 ton/year, respectively, and the yield was 21.48 ton/ha. Kampaeng Phet province was highest in the harvested area and production (86,159 ha and 1,887,862 ton/year), while Tak province was highest in yield (23.08 ton/ha).

Sugarcane was cultivated in 12 provinces including Lampang, Chiang Mai, Tak, Kampaeng Phet, Sukhothai, Phrae, Uttaradit, Phitsanulok, Phichit, Nakhon Sawan, Uthai Thani and Phetchabun provinces. The total harvested area and production were 317,058 ha and 24,742,466 ton/year, respectively, and the yield was 70.04 ton/ha. On the other hand, Nakhon Sawan province was highest in harvested area and production (91,842 ha and 7,508,447 ton/year), while Phetchabun province was highest in yield (83.05 ton/ha).

2) Northeastern region

Cassava was grown in 19 provinces, which comprises Loei, Nong Bua Lam Phu, Udon Thani, Nong Khai, Sakhon Nakhon, Nakhon Phanom, Mukdahan, Yasothon, Amnat charoen, Ubon Ratchathani, Si Sa Ket, Surin, Buri Ram, Maha Sarakham, Roi Et, Kalasin, KhonKaen, Chaiyaphum and Nakhon Ratchasima provinces. The total harvested area and production were 671,142 ha, 13,576,422 ton/year, respectively, and the yield was 20.23 ton/ha. Nakhon Ratchasima province was highest in harvested area and production (287,606 ha and 5,807,164 ton/year), while Kalasin province was highest in yield (21.08 ton/ha).

Sugarcane was grown in 18 provinces, which comprises Loei, Nong Bua Lam Phu, Udon Thani, Nong Khai, Sakhon Nakhon, Nakhon Phanom, Mukdahan, Yasothon, Amnat charoen, Si Sa Ket, Surin, Buri Ram, Maha Sarakham, Roi Et, Kalasin, KhonKaen, Chaiyaphum and Nakhon Ratchasima provinces. The total harvested area and production were 442,601 ha, 31,131,131 ton/year, respectively, and the yield was 70.34 ton/ha. In addition, Nakhon Ratchasima province was highest in harvested area and production (91,115 ha and 6,241,218 ton/year), while Khon Kaen province was highest in yield (75.80 ton/ha).

3) Central Plain

Cassava was grown in 13 provinces, which include Saraburi, Lop Buri, Chai Nat, Suphan Buri, Prachin Buri, Chachoengsao, Sa Kaeo, Chantaburi, Rayong, Chon Buri, Kanchanaburi, Ratchaburi and Phetchaburi provinces. The total harvested area and production were 357,468 ha, 7,467,593 ton/year, respectively, and the yield was 20.89 ton/ha. Furthermore, Sa Kaeo province was the highest in harvest area and production (59,892 ha and 1,218,292 ton/year), while Chon Buri province was the highest in yield (23.06 ton/ha).

Sugarcane was grown in 17 provinces, include of Saraburi, Lop Buri, Sing Buri, Chai Nat, Suphan Buri, Ang Thong, Prachin Buri, Chachoengsao, Sa Kaeo, Chantaburi, Rayong, Chon Buri, Nakhon Prathom, Kanchanaburi, Ratchaburi, Phetchaburi and Prachuap Kiri Khan provinces. The total harvested area and production were 383,766 ha, 27,935,052 ton/year, respectively, and the yield was 72.79 ton/ha. Furthermore, Kanchanaburi province was the highest in harvested area and production

(105,249 ha and 7,767,291 ton/year), while Suphan Buri province was the highest in yield (83.01 ton/ha).

4.1.1.2 Fertilizer application

The fertilizer application rate for cassava and sugarcane cultivation has been used according to the directions of the Department of Agriculture of Thailand (DOA). The N, P_2O_5 and K_2O Fertilizer application rate are applied at various crop growing stages to obtain high productivity that depends on soil types and fertility of the soil (DOA, 2005). The total fertilizer application for cassava and sugarcane cultivation by province is shown in Table 4.2. It was found that Nakhon Ratchasima, Chaiyaphum, Kampaeng Phet, Nakhon Sawan, Sa Kaeo and Kanchanaburi provinces used very high fertilizer applications, which is related to their large harvested area and high production.

To assess the grey WF in the process of crop cultivation, it is necessary to estimate the critical load of chemical substances (fertilizers) that will fully consume the assimilation capacity of the receiving water body (Franke *et al*., 2013), in other words, the critical load of chemical substances is multiplied by the percentage that reaches a water resource. This study proposed to focus on N-fertilizer application that was the most influential factor that affects the environment. Other chemical applications such as herbicides and pesticides have not been considered in this study. Fertilizer application has been applied to the crop fields as per soil type in the different provinces as shown in Table 4.2.

Table 4.2 Quantities of fertilizers applied to cassava and sugarcane fields as per soil type in different provinces.

Provinces	Soil types	Cassava field			Sugarcane field		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
		(ton/crop cycle)					
Northern							
Chiang Rai	clay	156	78	156	-	-	-
Phayao	loam	83	42	83	-	-	-
Lampang	loam	112	56	112	565	280	565
Chiang Mai	loam	-	-	-	46	23	46
Tak	clay	394	197	3,942	215	108	215
Kampaeng Phet	sand	8,616	4,308	8,616	3,752	7,571	3,752
Sukhothai	sandy loam	351	175	351	1,510	3,047	1,510
Phrae	sandy loam	72	36	72	19	37	19
Uttaradit	sandy loam	321	160	321	3,752	7,571	3,752
Phitsanulok	loam	2,783	1,392	2,783	1,510	3,047	1,510
Phichit	sandy loam	121	60	121	433	874	433
Nakhon Sawan	sandy loam	4,651	2,325	4,651	5,143	10,378	5,143
Uthai Thani	sandy loam	2,851	1,425	2,851	2,128	4,294	2,128
Phetchabun	clay	817	408	817	3,163	6,327	3,163
Northeastern							
Loei	loam	3,302	1,651	3,302	1,520	753	1,520
Nong Bua Lam Phu	loam	692	346	692	1,233	611	1,233
Udon Thani	loam	3,201	1,601	3,201	6,652	3,296	6,652
Nong Khai	sandy loam	629	315	629	127	63	127
Sakhon Nakhon	loam	1,487	743	1,487	474	235	474
Nakhon Phanom	sandy loam	490	245	490	110	55	110
Mukdahan	loam	1,770	885	1,770	1,752	868	1,752
Yasothon	loam	1,017	508	1,017	224	111	224
Amnat charoen	sand	635	318	635	164	81	164
Ubon Ratchathani	sandy loam	3,079	1,539	3,079	-	-	-
Si Sa Ket	sandy loam	1,405	702	1,405	98	49	98
Surin	sandy loam	955	478	955	2,956	1,465	2,956
Buri Ram	sandy loam	3,289	1,644	3,289	2,234	1,107	2,234
Maha Sarakham	sand	1,639	820	1,639	1,161	575	1,161
Roi Et	sandy loam	1,099	549	1,099	628	311	628
Kalasin	loam	4,141	2,071	4,141	4,937	2,446	4,937
KhonKaen	loam	3,458	1,729	3,458	8,980	4,450	8,980
Chaiyaphum	sandy loam	6,066	3,033	6,066	6,468	3,205	6,468
Nakhon Ratchasima	sandy loam	28,761	14,380	28,761	10,296	5,102	10,296
Central Plain							
Saraburi	clay	248	124	248	3,644	1,822	3,644
Lop Buri	clay	1,333	666	1,333	7,947	3,973	7,947
Sing Buri	sandy loam	-	-	-	823	408	823
Chai Nat	sand	1,147	573	1,147	969	480	969
Suphan Buri	sandy loam	585	293	585	7,693	3,812	7,693
Ang Thong	sandy loam	-	-	-	294	146	294
Prachin Buri	clay	1,300	650	1,300	210	105	210
Chachoengsao	clay	2,297	1,148	2,297	1,033	517	1,033

Table 4.2 (Continued).

Provinces	Soil types	Cassava field			Sugarcane field		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
		(ton/crop cycle)					
Sa Kaeo	sandy loam	5,989	2,995	5,989	3,711	1,839	3,711
Chantaburi	clay	1,942	971	1,942	404	202	404
Rayong	loam	2,246	1,123	2,246	421	209	421
Chon Buri	loam	4,625	2,313	4,625	1,898	941	1,898
Nakhon Prathom	loam	-	-	-	1,387	687	1,387
Kanchanaburi	sandy loam	5,565	2,782	5,565	11,893	5,894	11,893
Ratchaburi	loam	1,311	655	1,311	3,266	1,619	3,266
Phetchaburi	sandy loam	40	20	40	441	219	441
Prachuap Kiri Khan	loam	-	-	-	596	296	596

4.1.2 Data input for calculation of crop water requirements

4.1.2.1 Geographical data

The geographical data represents the crop location. In this study the geographical data were collected from the meteorological stations from each province that provide data about latitude, longitude and atlitude above mean sea level. These data are shown in Appendix A.

4.1.2.2 Climatic data

In order to estimate the ET_o by using the CROPWAT 8.0 program, the calculation based on the Penman-Monteith method that is recommended by FAO has been made following the assumptions given by Allen *et al*. (1998). Climatic data provided by the Thai Meteorological Department (TMD) revealed the climatic data by location and time of year. This study focused on the average climatic data of the six previous years during the period of 2008-2013. The data input included maximum temperature, minimum temperature, humidity, sunshine hours and wind speed as shown in Appendix B. In addition, the rainfall data was included to calculate the effective rainfall that effectively contributes to cover the CWR. The effective rainfall is defined as the part of the rainfall which varies from year to year, which is effectively used by the crop after rainfall losses due to surface run off and deep percolation that will be calculated by the USDA method (FAO, 2013b). The results of ET_o at each province can be seen in Table 4.3 and the effective rainfall in Table 4.4.

Table 4.3 Reference crop evapotranspiration in each province.

Provinces	Reference crop evapotranspiration (mm/day)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Northern													
Chiang Rai	2.83	3.57	4.00	4.79	4.62	4.11	3.63	3.61	3.74	3.50	3.23	2.60	3.69
Phayao	2.84	3.63	4.18	5.02	4.60	4.36	3.77	3.55	3.55	3.30	3.08	2.64	3.71
Lampang	2.62	3.32	3.82	4.59	4.31	4.00	3.44	3.37	3.21	3.09	2.77	2.59	3.43
Chiang Mai	3.09	3.78	4.34	5.24	4.76	4.14	3.68	3.52	3.68	3.53	3.42	2.79	3.83
Tak	3.13	4.26	5.05	6.09	4.75	4.34	4.29	3.73	3.75	3.35	3.34	3.02	4.09
Kampaeng Phet	3.03	3.69	4.04	4.88	4.60	4.13	3.59	3.52	3.48	3.51	3.39	2.91	3.73
Sukhothai	3.14	3.79	4.35	5.49	4.69	4.31	3.60	3.57	3.59	3.47	3.55	3.05	3.88
Phrae	2.77	3.54	4.09	4.89	4.49	4.12	3.51	3.36	3.50	3.32	3.14	2.72	3.62
Uttaradit	2.89	3.44	3.79	4.66	4.29	4.00	3.54	3.35	3.44	3.32	3.29	2.70	3.56
Phitsanulok	3.46	4.21	4.75	5.52	4.94	4.50	3.93	3.71	3.81	3.71	3.88	3.40	4.15
Phichit	2.95	3.69	4.13	5.02	4.77	4.25	3.63	3.57	3.48	3.55	3.42	2.96	3.78
Nakhon Sawan	3.31	4.14	4.77	5.28	4.80	4.26	3.79	3.73	3.59	3.62	3.49	3.24	4.00
Uthai Thani	3.67	4.15	4.01	4.62	4.80	4.30	3.82	3.63	3.48	3.64	3.82	3.70	3.97
Phetchabun	3.09	3.78	4.20	4.55	4.45	3.91	3.49	3.25	3.25	3.43	3.51	2.90	3.65
Northeastern													
Loei	3.15	4.04	4.62	5.03	4.49	4.12	3.71	3.71	3.61	3.55	3.54	3.04	3.59
Nong Bua Lam Phu	2.93	3.77	4.34	4.69	4.16	3.77	3.36	3.38	3.37	3.26	3.16	2.81	3.58
Udon Thani	3.25	3.99	4.68	5.14	4.50	4.04	3.59	3.58	3.56	3.53	3.55	3.15	3.88
Nong Khai	3.38	4.18	4.68	5.31	4.62	4.13	3.64	3.66	3.71	3.70	3.79	3.37	4.01
Sakhon Nakhon	3.22	3.96	4.50	4.88	4.32	3.93	3.74	3.66	3.59	3.82	3.59	3.14	3.86
Nakhon Phanom	3.33	3.94	4.40	4.67	4.12	3.69	3.55	3.44	3.36	3.71	3.71	3.34	3.77
Mukdahan	3.54	4.13	4.60	4.79	4.20	3.81	3.68	3.51	3.40	3.82	3.86	3.47	3.90
Yasothon	3.97	4.49	5.01	5.26	4.76	4.60	4.29	3.92	3.56	4.10	4.16	3.95	4.34
Amnat charoen	3.75	4.14	4.59	4.69	4.40	4.09	3.89	3.41	3.22	3.65	3.94	3.68	3.95
Ubon Ratchathani	4.30	4.83	5.44	4.45	4.54	4.44	4.42	3.87	3.57	4.09	4.41	4.10	4.45
Si Sa Ket	3.47	4.02	4.54	4.80	4.57	4.49	4.16	3.82	3.44	3.88	3.91	3.44	4.05

Table 4.3 (Continued).

Provinces	Reference crop evapotranspiration (mm/day)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Surin	3.69	4.28	4.90	5.11	4.58	4.43	4.18	3.63	3.43	3.81	3.79	3.58	4.12
Buri Ram	3.41	4.20	4.86	5.02	4.51	4.38	4.17	3.56	3.33	3.63	3.52	2.60	3.93
Maha Sarakham	3.66	4.32	4.72	5.15	4.76	4.69	4.36	3.99	3.62	3.37	3.95	3.60	4.18
Roi Et	3.70	4.28	5.32	5.32	4.85	4.68	4.30	4.03	3.59	4.09	4.11	3.77	4.34
Kalasin	4.18	4.73	5.36	5.61	5.00	4.41	4.08	3.79	3.56	4.10	4.26	4.04	4.43
KhonKaen	4.03	4.69	5.31	5.37	4.55	4.30	3.99	3.90	3.65	4.15	4.38	4.07	4.37
Chaiyaphum	3.63	4.24	4.80	4.94	4.26	3.93	3.79	3.71	3.53	3.85	3.97	3.60	4.02
Nakhon Ratchasima	3.55	4.13	4.57	4.85	4.65	4.43	4.08	3.85	3.46	3.60	3.79	3.61	4.05
Central Plain													
Saraburi	3.89	4.46	4.84	5.08	4.68	4.19	3.76	3.58	3.44	3.59	3.85	3.76	4.09
Lop Buri	3.77	4.20	4.63	5.09	4.80	4.20	3.75	3.62	3.50	3.62	4.10	3.97	4.10
Sing Buri	3.42	3.98	4.37	4.98	4.61	3.79	3.67	2.78	3.68	3.67	3.69	3.46	3.93
Chai Nat	3.25	3.94	4.34	5.16	4.80	4.22	3.95	3.82	3.61	3.60	3.66	3.34	3.97
Suphan Buri	3.29	3.84	4.22	4.83	4.45	3.67	3.57	3.72	3.64	3.57	3.54	3.26	3.80
Ang Thong	4.16	4.32	4.84	5.10	4.80	4.18	3.78	3.66	3.48	3.65	4.25	4.44	4.22
Prachin Buri	3.96	4.08	4.46	4.70	4.38	3.92	3.61	3.69	3.41	3.76	4.29	4.24	4.04
Chachoengsao	3.56	3.94	4.26	4.45	4.16	3.82	3.53	3.63	3.31	3.52	3.53	3.55	3.78
Sa Kaeo	3.58	3.99	4.31	4.58	4.24	3.81	3.51	3.60	3.31	3.55	3.60	3.54	3.80
Chantaburi	4.01	3.87	4.23	4.32	3.75	3.53	3.28	3.41	3.08	3.37	4.11	4.14	3.76
Rayong	3.71	4.23	4.48	4.88	4.44	4.36	4.09	4.10	3.64	3.61	3.82	3.76	4.09
Chon Buri	4.03	4.24	4.54	4.92	4.52	4.21	3.89	4.51	3.55	3.58	3.87	4.05	4.16
Nakhon Prathom	3.42	4.10	4.56	5.14	4.76	4.10	3.86	4.00	3.84	3.68	3.63	3.30	4.03
Kanchanaburi	3.18	3.81	4.12	4.68	4.31	3.48	3.39	3.58	3.56	3.53	3.40	3.11	3.68
Ratchaburi	3.85	4.41	4.72	5.21	4.46	3.93	3.63	3.80	3.56	3.40	3.64	3.82	4.04
Phetchaburi	4.14	4.72	5.13	5.45	4.84	4.35	4.02	4.15	3.86	3.66	4.16	4.33	4.40
Prachuap Kiri Khan	3.47	4.10	4.61	4.79	4.42	3.91	3.74	3.96	3.73	3.52	3.52	3.57	3.95

Table 4.4 Effective rainfall in each province.

Provinces	Effective rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Northern													
Chiang Rai	20.9	9.7	43.9	73.7	152.6	133.6	159.3	165.0	153.8	115.4	36.4	20.5	1,084.9
Phayao	16.3	7.7	28.7	63.2	131.4	90.0	117.2	131.8	130.7	104.6	43.6	12.3	877.4
Lampang	13.9	10.6	39.3	59.1	143.8	92.7	107.1	133.1	138.2	119.6	14.9	7.1	879.1
Chiang Mai	12.5	7.6	18.8	50.0	117.9	97.2	114.9	150.2	143.3	110.0	26.3	8.1	856.8
Tak	12.6	8.0	29.3	63.6	120.0	104.4	111.1	87.7	144.7	108.0	16.7	6.8	812.9
Kampaeng Phet	4.7	16.3	46.3	48.5	132.4	134.9	147.2	127.3	155.7	140.1	19.6	14.4	987.3
Sukhothai	15.1	6.2	28.3	71.5	126.4	130.6	122.1	132.8	158.6	145.4	16.9	16.5	970.5
Phrae	20.0	6.8	31.0	83.9	119.0	128.2	128.9	143.4	143.8	58.8	27.1	11.5	902.5
Uttaradit	8.0	2.1	32.3	77.0	124.2	142.0	136.1	155.5	148.4	109.8	12.2	5.0	952.6
Phitsanulok	9.5	12.2	28.8	54.7	111.0	123.3	137.0	151.3	158.8	116.8	34.4	13.7	951.4
Phichit	15.1	5.4	31.0	67.3	96.1	136.5	141.1	143.1	151.7	103.8	26.7	15.3	933.1
Nakhon Sawan	12.3	9.1	37.3	67.6	127.4	104.0	115.0	134.0	155.3	147.6	23.2	5.2	937.8
Uthai Thani	20.0	15.1	34.2	65.5	121.1	109.6	111.3	137.9	159.4	135.9	33.8	4.8	948.7
Phetchabun	16.0	17.2	54.6	66.8	133.1	99.6	130.5	136.6	152.6	79.3	14.0	11.7	912.0
Northeastern													
Loei	13.5	12.3	41.8	96.7	136.6	106.2	137.3	150.9	155.5	100.7	12.3	21.2	985.0
Nong Bua Lam Phu	10.6	12.7	44.7	104.4	121.5	99.6	130.8	124.5	154.4	102.2	11.4	15.7	932.4
Udon Thani	13.7	14.8	37.6	66.6	139.4	130.7	148.9	152.3	149.9	78.0	34.3	10.0	976.2
Nong Khai	18.9	14.4	62.2	64.2	151.8	150.5	161.6	161.5	155.1	81.3	35.1	11.1	1,067.7
Sakhon Nakhon	15.2	11.1	52.0	116.2	149.6	149.2	161.6	158.9	147.3	70.8	9.9	9.8	1,051.7
Nakhon Phanom	6.5	14.0	51.1	83.4	158.6	162.0	183.3	173.1	151.8	66.6	3.3	6.0	1,059.6
Mukdahan	3.3	2.9	37.1	67.4	148.2	148.3	149.7	157.0	141.2	64.9	13.7	6.5	941.1
Yasothon	17.5	8.3	30.5	67.7	130.9	101.4	139.7	150.3	155.4	96.1	16.0	3.6	917.3
Amnat charoen	4.3	7.3	35.0	79.3	139.0	119.4	152.0	156.4	162.8	84.9	10.9	11.0	962.3
Ubon Ratchathani	6.2	3.0	28.3	75.3	146.6	120.3	155.8	160.0	163.3	91.9	27.5	18.0	996.1
Si Sa Ket	4.3	3.9	16.0	89.0	144.7	99.3	143.5	142.7	160.0	105.6	22.9	7.9	939.8

Table 4.4 (Continued).

Provinces	Effective rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Surin	5.5	15.4	37.4	76.6	137.8	121.0	136.0	146.3	160.0	102.0	31.1	4.8	974.2
Buri Ram	15.8	11.5	34.1	74.3	137.8	114.4	132.8	154.7	152.6	93.6	21.1	1.9	944.6
Maha Sarakham	18.2	12.3	31.3	81.6	137.6	81.6	144.1	150.1	155.9	70.7	25.4	4.0	912.7
Roi Et	17.4	6.4	33.7	60.2	137.7	108.7	135.4	151.0	156.0	83.6	16.5	3.7	910.3
Kalasin	19.9	9.5	24.7	63.5	119.7	130.4	137.1	152.2	151.3	66.3	14.2	6.5	895.4
KhonKaen	20.1	4.2	33.0	96.4	107.6	94.7	141.7	143.9	150.4	66.9	22.2	5.4	886.5
Chaiyaphum	16.3	5.5	62.8	79.7	120.1	96.0	128.3	151.8	157.1	106.0	19.2	11.7	954.4
Nakhon Ratchasima	19.6	4.1	49.7	101.0	106.5	74.5	125.7	121.7	151.9	133.6	25.3	0.4	914.0
Central Plian													
Saraburi	21.9	6.7	32.7	83.6	105.0	84.7	89.4	38.0	156.5	136.2	5.4	4.2	864.2
Lop Buri	2.7	8.6	25.2	76.7	100.7	115.9	96.3	111.5	161.0	128.5	14.5	0.7	842.1
Sing Buri	0.4	1.7	15.2	31.8	104.2	78.5	86.6	96.5	143.3	132.5	49.2	3.1	743.0
Chai Nat	6.1	5.5	18.3	42.0	129.7	122.5	102.1	115.5	156.0	141.3	10.5	3.0	852.6
Suphan Buri	4.7	17.1	24.7	41.8	81.9	91.4	87.6	96.7	143.6	135.0	15.7	7.8	748.1
Ang Thong	1.0	11.2	32.1	59.3	101.8	100.1	127.7	136.4	154.3	97.9	26.0	5.5	853.4
Prachin Buri	8.4	16.8	47.7	82.7	133.4	153.3	156.6	164.6	174.7	115.1	22.2	1.1	1,076.5
Chachoengsao	24.9	17.8	82.3	109.9	122.6	121.4	146.7	133.9	162.1	141.1	26.7	4.0	1,093.3
Sa Kaeo	9.9	32.7	35.1	98.5	124.3	136.9	147.8	147.5	161.6	137.6	20.4	1.7	1,053.9
Chantaburi	31.8	55.6	87.2	121.3	169.3	168.2	184.3	165.3	183.8	153.0	61.0	5.2	1,386.0
Rayong	41.2	36.3	57.9	72.1	127.0	130.4	150.2	129.2	154.1	140.6	32.5	2.3	1,073.8
Chon Buri	19.6	20.6	61.4	77.6	105.4	104.1	131.3	145.2	158.2	147.7	41.8	6.0	1,018.8
Nakhon Prathom	1.8	12.5	15.7	55.8	105.7	112.1	81.0	100.4	149.2	148.7	37.4	2.2	822.6
Kanchanaburi	2.9	33.1	73.5	40.9	111.3	96.5	101.0	95.2	148.5	137.8	50.0	2.4	893.0
Ratchaburi	3.2	8.5	39.6	31.8	99.2	95.2	120.1	96.2	128.7	146.3	61.1	6.8	836.5
Phetchaburi	24.1	3.9	45.8	41.1	88.3	70.4	81.0	80.1	94.0	156.8	71.4	3.6	760.3
Prachuap Kiri Khan	35.7	26.2	66.9	53.8	64.1	81.3	111.7	49.7	91.5	125.5	97.0	18.3	821.7

4.1.2.3 Crop characteristics

A variety of crop characteristics should be input to the CROPWAT 8.0 program to calculate the ET. Crop characteristics include length of individual growth stages, rooting depth, critical depletion fraction, crop height and crop coefficient, all of which data have been taken from FAO, provided by Allen *et al*. (1998). In addition, the yield response factor was available from FAO, provided by Steduto *et al*. (2012). Moreover, the most representative planting and harvest dates were taken used as obtained from Thai farmers. The cassava planting date mostly starts in the early rain season, however, in this study it was determined as 1st May and the harvest date as 25th April, with a growing period of 360 days. On the other hand, sugarcane planting date was also started on 1st May and the harvest date on 16th March, with a growing period of 320 days. The crop characteristics of cassava and sugarcane are presented in Table 4.5.

Table 4.5 Crop characteristics of cassava and sugarcane.

Growing stage	Initial	Develop	Middle	Late	Total
Cassava					
Length (days)	150	40	110	60	360
crop coefficient; K_c	0.30	-	1.10	0.50	-
Rooting depth (m)	0.70	-	-	1.10	-
Critical depletion (%)	40	40	40	40	-
Yield response; K_y	0.60	0.33	0.70	0.20	1.10
Crop height (m)	-	-	1.50	-	-
Sugarcane					
Length (days)	30	50	180	60	320
crop coefficient; K_c	0.40	-	1.25	0.75	-
Rooting depth (m)	1.20	-	-	2.00	-
Critical depletion (%)	65	65	65	65	-
Yield response; K_y	0.75	1.20	0.50	0.10	1.20
Crop height (m)	-	-	3.00	-	-

4.1.2.4 Soil data

The soil series and soil types are defined by the Land Development Department (LDD). Cassava and sugarcane crops are cultivated with specific soil series and soil types, which are mostly sandy loam and loam soils. The soil data set are essential data input in order for the CROPWAT 8.0 program to calculate the ET. To estimate under the irrigation schedule-option, the soil data set should provide the value of the initial available soil moisture, including the total available soil moisture, maximum rain infiltration rate, maximum rooting depth and initial soil moisture depletion. All these different data depend on the soil series and soil types. The data for the total available soil moisture are associated with the soil series and soil types according to Nilpunt (2013), whereas the maximum rain infiltration rate is based on Israelsen *et al*. (1980). Furthermore, the maximum rooting depth and initial soil moisture depletion were determined at 0.6 m and 50%, respectively. Soil data and their associated data input in the CROPWAT 8.0 program and output data are shown in Appendix C.

4.1.3 Water footprint of cassava cultivation

4.1.3.1 Green and blue crop water footprint

1) Crop water requirements

The CWR refer to the amount of water needed to compensate for water lost through evapotranspiration which is equal to the ET. The ET was calculated by using the CROPWAT 8.0 program that required various data including climate, rainfall, crop characteristics, soil, the corresponding geographical data, and the planting and harvest dates. The data from the CROPWAT 8.0 program that consisted of ET_o, effective rainfall, ET_c and ET_a, respectively. The ET is normally expressed in mm unit per day which is the amount of water lost from a cropped surface in units of water depth (Allen *et al.*, 1998). The resulting ET was calculated under both different options, which were the CWR-option and the irrigation schedule-option. The ET_c estimated under the CWR-option, can be run with climate, effective rainfall and crop data set, which was estimated in a ten days' time step over the total growing season. On the other hand, ET_a was estimated under the irrigation schedule-option which required the same data as that of ET_c and, in addition, the soil data, which was estimated over the total growing season using the daily soil water balance approach. Generally, ET_a may be smaller than ET_c due to the crops being grown under non-standard conditions (Hoekstra *et al.*, 2011). The results of ET_c and ET_a are estimated distinguishing ET_{green} and ET_{blue} as displayed in Table 4.6.

Table 4.6 Crop evapotranspiration of cassava cultivation estimated under the CWR-option (1) and irrigation schedule-option (2).

Provinces	Options	Crop evapotranspiration ET_{green} (mm/growing period)	Crop evapotranspiration ET_{blue} (mm/growing period)	Crop evapotranspiration $ET_{c\ or\ a}$* (mm/growing period)
Northern				
Chiang Rai	1	437	380	817
	2	426	389	815
Phayao	1	407	424	831
	2	392	436	828
Lampang	1	367	403	770
	2	354	413	767
Tak	1	383	527	910
	2	357	550	907
Kampaeng Phet	1	385	433	818
	2	361	455	816
Sukhothai	1	391	473	864
	2	365	497	862
Phrae	1	380	420	800
	2	362	436	798

Table 4.6 (Continued).

Provinces	Options	Crop evapotranspiration		
		ET_{green}	ET_{blue}	$ET_{c\ or\ a}$*
		(mm/growing period)		
Uttaradit	1	352	429	781
	2	354	424	778
Phitsanulok	1	407	533	940
	2	395	543	938
Phichit	1	393	434	827
	2	382	443	825
Nakhon Sawan	1	398	496	894
	2	393	498	891
Uthai Thani	1	431	488	919
	2	385	532	917
Phetchabun	1	388	437	825
	2	381	442	823
Northeastern				
Loei	1	414	475	889
	2	392	496	888
Nong Bua Lam Phu	1	391	428	819
	2	413	404	817
Udon Thani	1	398	498	896
	2	394	500	894
Nong Khai	1	435	493	928
	2	391	535	926
Sakon Nakhon	1	401	476	877
	2	416	459	875
Nakhon Phanom	1	360	518	878
	2	335	541	876
Mukdahan	1	337	580	917
	2	329	585	914
Yasothon	1	392	640	1,032
	2	382	648	1,030
Amnat Charoen	1	363	579	942
	2	284	655	939
Ubon Ratchathani	1	402	688	1,090
	2	388	699	1,087
Si Sa Ket	1	373	548	921
	2	377	541	918
Surin	1	408	550	958
	2	386	569	955
Buri Ram	1	387	486	873
	2	368	503	871
Maha Sarakham	1	403	554	957
	2	401	553	954

Table 4.6 (Continued).

Provinces	Options	Crop evapotranspiration		
		ET_{green}	ET_{blue}	$ET_{c\ or\ a}$*
		(mm/growing period)		
Roi Et	1	384	610	994
	2	368	624	992
Kalasin	1	372	706	1,078
	2	352	724	1,076
Khon Kaen	1	400	658	1,058
	2	412	643	1,055
Chaiyaphum	1	423	511	934
	2	397	535	932
Nakhon Ratchasima	1	429	495	924
	2	391	530	921
Central Plain				
Saraburi	1	390	579	969
	2	388	579	967
Lop Buri	1	366	577	943
	2	365	576	941
Chai Nat	1	334	537	871
	2	273	596	869
Suphan Buri	1	350	502	852
	2	336	515	850
Prachin Buri	1	401	553	954
	2	380	573	952
Chachoengsao	1	459	413	872
	2	440	430	870
Sa Kaeo	1	403	471	875
	2	413	460	873
Chantaburi	1	526	368	894
	2	481	412	892
Rayong	1	485	415	900
	2	484	414	898
Chon Buri	1	471	468	939
	2	420	517	937
Kanchanaburi	1	434	391	824
	2	425	397	822
Ratchaburi	1	393	549	942
	2	465	474	939
Phetchaburi	1	454	586	1,040
	2	433	605	1,038

Remark * = ET_c was the ET estimated under the CWR-option (1), ET_a was the ET estimated under the irrigation schedule-option (2).

The results which expressed the ET_c (option 1) were slightly higher than ET_a (option 2), which can be explained by the fact that the cassava was grown in non-standard conditions, and soil conditions and soil water stress affected the crop transpiration that made the ET_a low in option 2. When water moves into the soil, the water holding capacity of the soil and the ability of the crops to use the water can be influenced by different factors, such as the physical condition, fertility and biological status of the soil (Hoekstra *et al.*, 2011). The results show that the blue component is higher than the green, which means that high volumes of irrigation water have been used on the cassava field which is greater than the availability of the effective rainfall. However, the ET results estimated under the irrigation schedule-option is the actual amount of water that should be provided for irrigation according to the scheduling practices of the farmers.

2) The evaporation of crop water use and the water footprint

To assess the evaporation of CWU and WF of cassava cultivation, it is necessary to classify them into green and blue components. Table 4.7 shows that the average of CWU_{eva} and WF_{eva} was largest in the Northeastern region, followed by the Central Plain and Northern region, respectively. In most provinces that the blue component was larger than the green, especially in the dry season (October to February) because the effective rainfall was insufficient for field crop, so the amount of water required was supplied by irrigation water.

In the Northern region, the average of CWU_{green}, CWU_{blue}, and CWU_{eva} estimated under the CWR-option was 3,935, 4,521 and 8,456 m^3/ha, respectively, while under the irrigation schedule-option it was 3,773, 4,659 and 8,432 m^3/ha, respectively, except for Chiang Rai province which had a higher level of green than blue because Chiang Rai province receives intensive rainfall. The average of WF_{green}, WF_{blue} and WF_{eva} estimated under the CWR-option was 183, 210 and 393 m^3/ton, whereas under the irrigation schedule-option it was at 176, 217 and 393 m^3/ton. The three provinces with the largest CWU_{eva} and WF_{eva} estimated under the irrigation schedule-option were Phitsanulok, Uthai Thani and Tak provinces, respectively.

In the Northeastern region, the average CWU_{green}, CWU_{blue}, and CWU_{eva} estimated under the CWR-option was 3,932, 5,522 and 9,454 m^3/ha, respectively, while under the irrigation schedule-option it was 3,777, 5,654 and 9,431 m^3/ha, respectively. The blue component was higher than the green component. Furthermore, the average of WF_{green}, WF_{blue} and WF_{eva} estimated under CWR-option was 194, 273 and 467 m^3/ton, respectively, while under the irrigation schedule-option it was 187, 280 and 467 m^3/ton, respectively. Finally, the top three CWU_{eva} and WF_{eva} estimated under the irrigation schedule-option were Ubon Ratchathani, Kalasin, and Khon Kaen provinces, respectively.

In the Central Plain, the average CWU_{green}, CWU_{blue}, and CWU_{eva} estimated under the CWR-option was 4,205, 4,930 and 9,135 m^3/ha, respectively, whereas under the irrigation schedule-option it was 4,079, 5,036 and 9,115 m^3/ha, respectively. The blue component was higher than the green component, but Chachoengsao, Chantaburi, Rayong and Kanchanaburi provinces showed that the green component was slightly higher than blue component, because these provinces have received intensive rainfall that was affected by the monsoon. The average WF_{green}, WF_{blue} and WF_{eva} estimated under the CWR-option was 201, 236 and 437 m^3/ton, while under the irrigation schedule-option it was 195, 241 and 436 m^3/ton. Furthermore, the three provinces with the highest CWU_{eva} and WF_{eva} which were estimated under the irrigation schedule-option were Phetchaburi, Saraburi and Prachin Buri provinces, respectively.

Table 4.7 The evaporation of crop water use and the water footprint of cassava cultivation estimated under the CWR-option (1) and irrigation schedule-option (2).

Provinces	Opt.*	CWU_{green}	CWU_{blue}	CWU_{eva}	WF_{green}	WF_{blue}	WF_{eva}
		m^3/ha			m^3/ton		
Northern							
Chiang Rai	1	4,367	3,799	8,166	223	194	417
	2	4,255	3,887	8,142	217	198	415
Phayao	1	4,056	4,244	8,300	199	208	407
	2	3,919	4,356	8,275	192	214	406
Lampang	1	3,665	4,025	7,690	185	203	388
	2	3,542	4,125	7,667	178	208	386
Tak	1	3,832	5,272	9,104	166	228	394
	2	3,572	5,503	9,075	155	238	393
Kampaeng Phet	1	3,847	4,332	8,179	176	198	374
	2	3,610	4,546	8,156	165	207	372
Sukhothai	1	3,907	4,733	8,640	204	247	451
	2	3,646	4,967	8,613	190	259	449
Phrae	1	3,798	4,200	7,998	193	213	406
	2	3,617	4,356	7,973	184	221	405
Uttaradit	1	3,516	4,287	7,803	171	209	380
	2	3,543	4,242	7,785	173	207	380
Phitsanulok	1	4,070	5,328	9,398	190	249	439
	2	3,946	5,426	9,372	185	254	439
Phichit	1	3,933	4,340	8,273	188	207	395
	2	3,816	4,432	8,248	182	212	394
Nakhon Sawan	1	3,978	4,961	8,939	188	235	423
	2	3,933	4,980	8,913	186	236	422
Uthai Thani	1	4,311	4,882	9,193	206	233	439
	2	3,845	5,324	9,169	184	254	438
Phetchabun	1	3,879	4,372	8,251	177	200	377
	2	3,811	4,419	8,230	174	202	376
Average	1	3,935	4,521	8,456	183	210	393
	2	3,773	4,659	8,432	176	217	393
Northeastern							
Loei	1	4,144	4,752	8,896	199	229	428
	2	3,916	4,959	8,875	188	239	427
Nong Bua Lam Phu	1	3,909	4,284	8,193	193	212	405
	2	4,133	4,041	8,174	204	200	404
Udon Thani	1	3,982	4,982	8,964	196	246	442
	2	3,941	4,999	8,940	194	246	440

Table 4.7 (Continued).

Provinces	Opt.*	CWU$_{green}$	CWU$_{blue}$	CWU$_{eva}$	WF$_{green}$	WF$_{blue}$	WF$_{eva}$
		m^3/ha			m^3/ton		
Nong Khai	1	4,353	4,925	9,278	222	251	473
	2	3,905	5,347	9,252	199	273	472
Sakon Nakhon	1	4,013	4,757	8,770	214	253	467
	2	4,157	4,589	8,746	221	244	465
Nakhon Phanom	1	3,598	5,183	8,781	187	270	457
	2	3,353	5,407	8,760	175	281	456
Mukdahan	1	3,371	5,795	9,166	173	297	470
	2	3,293	5,852	9,145	169	300	469
Yasothon	1	3,920	6,403	10,323	190	311	501
	2	3,824	6,475	10,299	185	314	499
Amnat Charoen	1	3,631	5,792	9,423	177	282	459
	2	2,844	6,554	9,398	139	319	458
Ubon Ratchathani	1	4,017	6,877	10,894	202	346	548
	2	3,876	6,992	10,868	195	351	546
Si Sa Ket	1	3,726	5,477	9,203	179	263	442
	2	3,767	5,414	9,181	181	260	441
Surin	1	4,075	5,501	9,576	201	271	472
	2	3,860	5,691	9,551	190	280	470
Buri Ram	1	3,868	4,860	8,728	181	227	408
	2	3,681	5,025	8,706	172	235	407
Maha Sarakham	1	4,033	5,537	9,570	205	282	487
	2	4,014	5,532	9,546	204	282	486
Roi Et	1	3,842	6,097	9,939	190	302	492
	2	3,682	6,235	9,917	182	308	490
Kalasin	1	3,723	7,058	10,781	177	335	512
	2	3,515	7,238	10,753	167	343	510
Khon Kaen	1	3,998	6,578	10,576	205	338	543
	2	4,119	6,429	10,548	211	330	541
Chaiyaphum	1	4,226	5,112	9,338	211	255	466
	2	3,969	5,349	9,318	198	267	465
Nakhon Ratchasima	1	4,285	4,951	9,236	212	245	457
	2	3,911	5,303	9,214	194	262	456
Average	1	3,932	5,522	9,454	194	273	467
	2	3,777	5,654	9,431	187	280	467
Central plain							
Saraburi	1	3,902	5,791	9,693	195	289	484
	2	3,875	5,793	9,668	193	289	482
Lop Buri	1	3,664	5,768	9,432	180	283	463
	2	3,650	5,759	9,409	179	283	462
Chai Nat	1	3,342	5,371	8,713	145	316	461
	2	2,733	5,958	8,691	145	316	461

Table 4.7 (Continued).

Provinces	Opt.*	CWU_{green}	CWU_{blue}	CWU_{eva}	WF_{green}	WF_{blue}	WF_{eva}
			m^3/ha			m^3/ton	
Suphan Buri	1	3,502	5,020	8,522	180	258	438
	2	3,356	5,147	8,503	173	265	438
Prachin Buri	1	4,013	5,531	9,544	191	263	454
	2	3,796	5,728	9,524	180	272	452
Chachoengsao	1	4,587	4,134	8,721	213	192	405
	2	4,402	4,299	8,701	205	200	405
Sa Kaeo	1	4,033	4,713	8,746	198	232	430
	2	4,130	4,596	8,726	231	198	429
Chantaburi	1	5,261	3,680	8,941	253	177	430
	2	4,808	4,115	8,923	231	198	429
Rayong	1	4,852	4,145	8,997	225	192	417
	2	4,842	4,137	8,979	224	192	416
Chon Buri	1	4,709	4,682	9,391	204	203	407
	2	4,199	5,171	9,370	182	224	406
Kanchanaburi	1	4,336	3,905	8,241	217	195	412
	2	4,248	3,972	8,220	212	198	410
Ratchaburi	1	3,925	5,492	9,417	196	275	471
	2	4,653	4,740	9,393	233	237	470
Phetchaburi	1	4,542	5,861	10,403	217	280	497
	2	4,331	6,047	10,378	207	289	496
Average	1	4,205	4,930	9,135	201	236	437
	2	4,079	5,036	9,115	195	241	436
Average of Thailand	**1**	**4,012**	**5,062**	**9,074**	**194**	**245**	**439**
	2	**3,863**	**5,188**	**9,051**	**187**	**251**	**438**

Remark * = options.

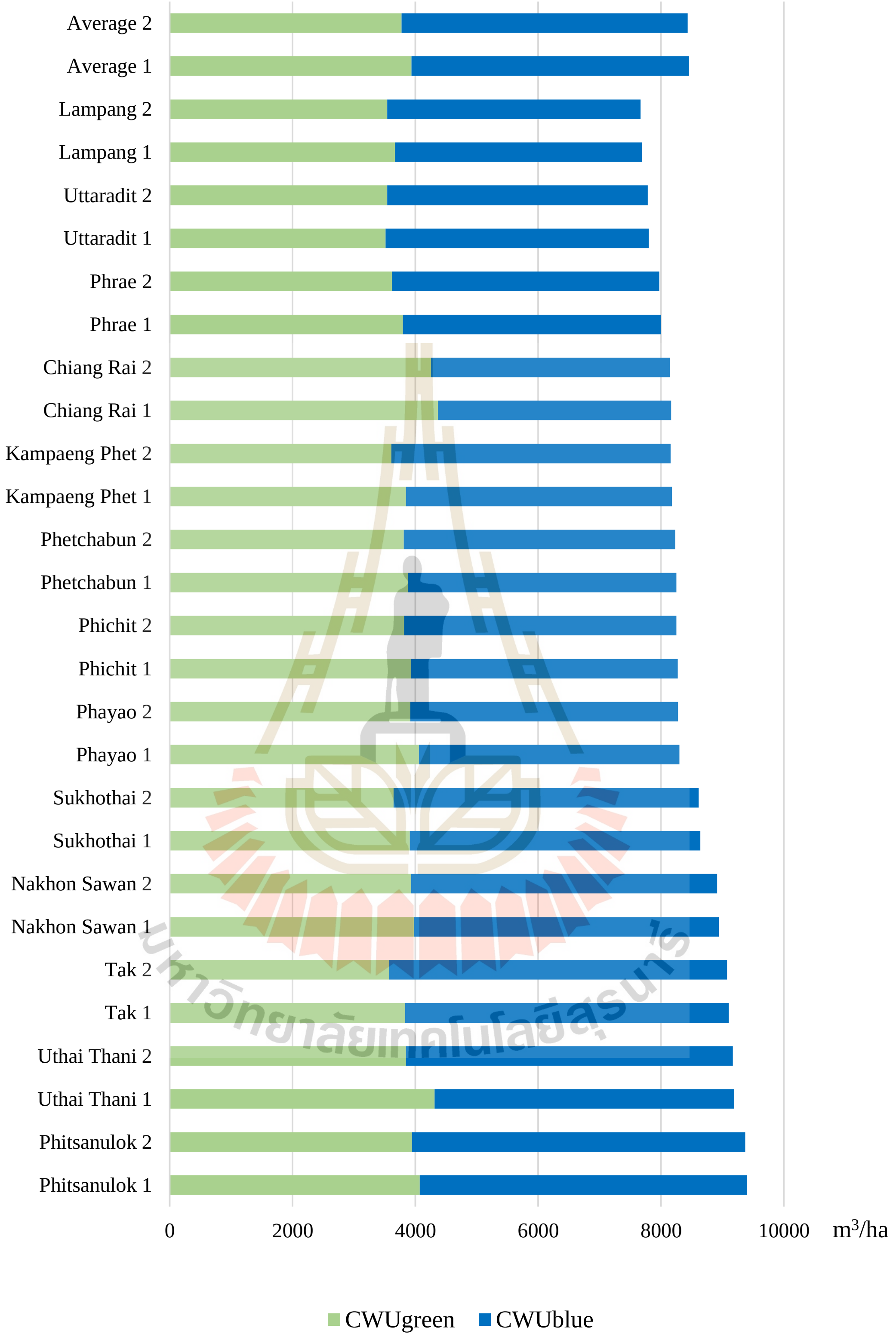


Figure 4.1 The CWU of cassava cultivation in the Northern region estimated under the CWR-option (1) and the irrigation schedule-option (2).

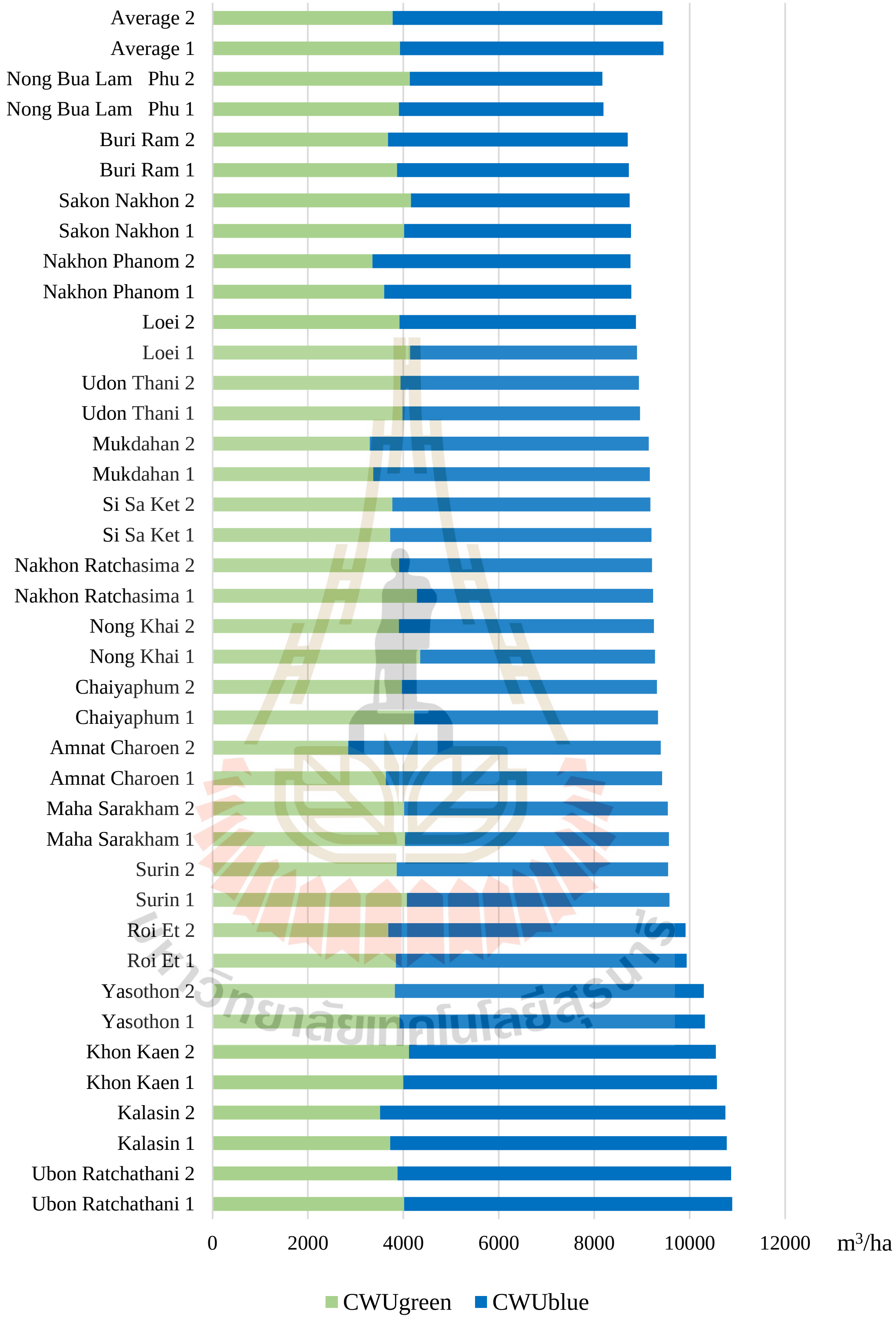


Figure 4.2 The CWU of cassava cultivation in the Northeastern region estimated under the CWR-option (1) and the irrigation schedule-option (2).

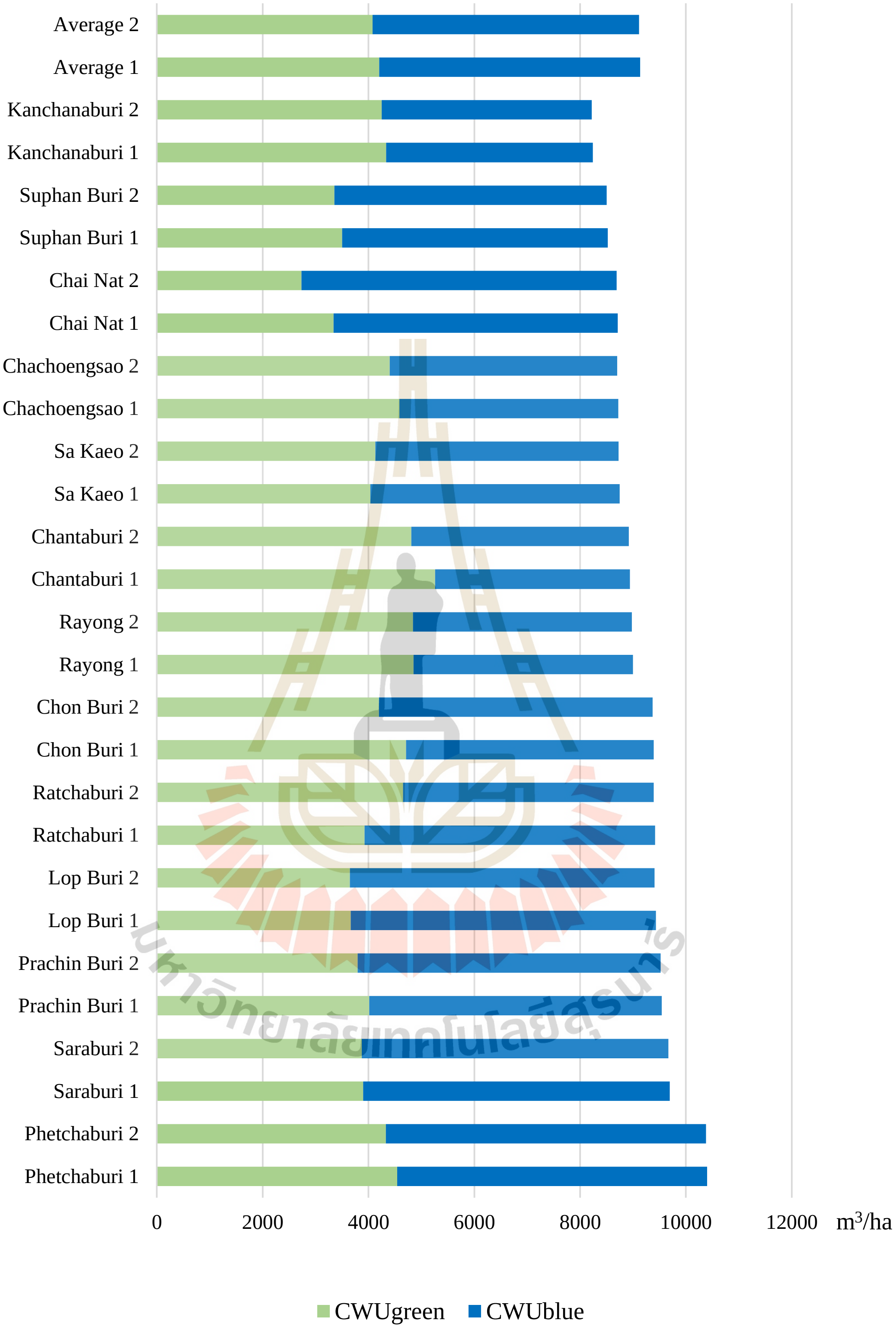


Figure 4.3 The CWU of cassava cultivation in the Central Plain estimated under the CWR-option (1) and the irrigation schedule-option (2).

4.1.3.2 Grey water footprint

Table 4.2 shows the amount of fertilizers used for cassava crops. 10% of total N-fertilizer was used to estimate the amount of pollutants reaching the water resources that create the grey component. The WF_{grey} per unit of crop is shown by an equation (3.11), where the maximum allowable concentration (C_{max}) with reference to the standard quality of Thai water is due to the ambient water quality standard for nitrogen that uses 5 mg/L, as recommended by the Office of Natural Resources and Environmental Policy and Planning (ONPE) (2013). Furthermore, because of lack of appropriate data about the natural concentration in the receiving water bodies (C_{nat}), it was assumed to be zero since no local information was available. The average of WF_{grey} of cassava cultivation is shown in Table 4.8. The results showed that Kampaeng Phet province from the Northern region, Nakhon Ratchasima province from the Northeastern region and Sa Kaeo province from the Central Plain were the major areas which consumed the highest amount of N-fertilizer since these provinces had very large harvested crop areas. The averages for WF_{grey} showed that the Northeastern region was the highest followed by the Northern and Central Plain, which were 99, 86 and 79 m^3/ton, respectively. However, the WF_{grey} has been discussed the quantity of N-fertilizer applied to the field depended on the soil series and location of soil types. For cassava plantation, sandy and sandy loam soils should be given more N-fertilizer applications than for clay soil.

Table 4.8 Quantities of nitrogen fertilizer applied to the field and grey water footprint of cassava cultivation.

Provinces	N-fertilizer (ton/crop cycle)	Grey WF (m^3/ton)
Northern		
Chiang Rai	156	51
Phayao	83	98
Lampang	112	101
Tak	394	43
Kampaeng Phet	8,616	91
Sukhothai	351	104
Phrae	72	102
Uttaradit	321	98
Phitsanulok	2,783	94
Phichit	121	96
Nakhon Sawan	4,651	95
Uthai Thani	2,851	96
Phetchabun	817	46
Average	-	86
Northeastern		
Loei	3,302	96
Nong Bua Lam Phu	692	99
Udon Thani	3,201	99
Nong Khai	629	102
Sakon Nakhon	1,487	107
Nakhon Phanom	490	104
Yasothon	1,017	97
Amnat Charoen	635	97
Ubon Ratchathani	3,079	100
Si Sa Ket	1,405	96
Surin	955	98
Buri Ram	3,289	93
Maha Sarakham	1,639	102
Roi Et	1,099	99
Kalasin	4,141	95
Khon Kaen	3,458	103
Chaiyaphum	6,066	100
Nakhon Ratchasima	28,761	99
Average	-	99

Table 4.8 (Continued)**.**

Provinces	N-fertilizer (ton/crop cycle)	Grey WF (m^3/ton)
Central Plain		
Saraburi	248	50
Lop Buri	1,333	49
Chai Nat	1,147	106
Suphan Buri	585	103
Prachin Buri	1,300	48
Chachoengsao	2,297	47
Sa Kaeo	5,989	98
Chantaburi	1,942	48
Rayong	2,246	93
Chon Buri	4,625	87
Kanchanaburi	5,565	100
Ratchaburi	1,311	100
Phetchaburi	40	96
Average	-	79
Average of Thailand	-	**90**

4.1.3.3 Total water footprint of cassava cultivation

In order to assess the total WF of cassava cultivation divided into three regions of Thailand, namely the Northern, Northeastern and Central Plain, during 2008-2013, is the summation of the green, blue (Table 4.7) and grey (Table 4.8) WFs. This study focused only on the green and blue WFs estimated under the irrigation schedule-option because it was calculated based on a soil water budget that was the actual water requirements of the field irrigation method.

The WF result for the three regions showed that the average WF_{total} was highest in the Northeastern region, which was at 566 m^3/ton (34, 49 and 17% of green, blue and grey), followed by the Central Plain at 515 m^3/ton (38, 47 and 15% of green, blue and grey) and the Northern at 479 m^3/ton (37, 46 and 17% of green, blue and grey), respectively. However, the average WF for cassava cultivation in the whole country was 528 m^3/ton (36, 47 and 17% of green, blue and grey)

With regard to each of the regions, the Northern region was found to have the top three WF_{total} decreases as follows: Sukhothai (553 m^3/ton), Uthai Thani (534 m^3/ton) and Phitsanulok (533 m^3/ton). In the Northeastern region, the top three WF_{total} were Ubon Ratchathani (646 m^3/ton), Khon Kaen (644 m^3/ton) and Kalasin (605 m^3/ton), and in the Central Plain they were Phetchaburi (592 m^3/ton), Ratchaburi (570 m^3/ton) and Chai Nat (567 m^3/ton).

Additionally, the blue component was the most intensively grown crop followed by the green and grey as a result of the high volume of irrigation water used on the fields. For these results, because when we set the cassava planting date on 1st May, the development and middle growing stages of cassava cultivation (these stages required high amountd of water) that corresponded with the period of the dry season (October to February), the effective rainfall was not enough for the crop grown, so a high volume of irrigation water (blue water) was used to compensate on the crop fields. With regard to the crop planting date which is important for the water scheduling plan, due to the initial crop growing stage being for a relatively long time duration (150 days), so that if we determine the planting date is at the beginning of February or March, we should be certain that the development and middle crop growing stage will correspond to the rainy season (June to November), when the irrigation water requirement will be low. Although large agricultural areas may have various other crops planted, a high volume of water use must be used to contribute to the agricultural sector that could be affected by water shortages and water stress in their areas. The results of this study are very useful for the policies and management of appropriate water resources.

Table 4.9 Water footprint of cassava cultivation estimated under the irrigation schedule-option.

Provinces	Water footprint of cassava cultivation (m^3/ton)			
	Green	Blue	Grey	Total
Northern				
Chiang Rai	217	198	51	466
Phayao	192	214	98	504
Lampang	178	208	101	487
Tak	155	238	43	436
Kampaeng Phet	165	207	91	463
Sukhothai	190	259	104	553
Phrae	184	221	102	507
Uttaradit	173	207	98	478
Phitsanulok	185	254	94	533
Phichit	182	212	96	490
Nakhon Sawan	186	236	95	517
Uthai Thani	184	254	96	534
Phetchabun	174	202	46	422
Average	176	217	86	479
Northeastern				
Loei	188	239	96	523
Nong Bua Lam Phu	204	200	99	503
Udon Thani	194	246	99	539
Nong Khai	199	273	102	574
Sakon Nakhon	221	244	107	572
Nakhon Phanom	175	281	104	560
Mukdahan	169	300	103	572
Yasothon	185	314	97	596
Amnat Charoen	139	319	97	555
Ubon Ratchathani	195	351	100	646
Si Sa Ket	181	260	96	537
Surin	190	280	98	568
Buri Ram	172	235	93	500
Maha Sarakham	204	282	102	588
Roi Et	182	308	99	589
Kalasin	167	343	95	605
Khon Kaen	211	330	103	644
Chaiyaphum	198	267	100	565
Nakhon Ratchasima	194	263	99	556
Average	187	280	99	566
Central Plain				
Saraburi	193	289	50	532
Lop Buri	179	283	49	511
Chai Nat	145	316	106	567
Suphan Buri	173	265	103	541

Table 4.9 (Continued).

Provinces	Water footprint of cassava cultivation (m^3/ton)			
	Glue	Blue	Grey	Total
Prachin Buri	180	272	48	500
Chachoengsao	205	200	47	452
Sa Kaeo	203	226	98	527
Chantaburi	231	198	48	477
Rayong	224	192	93	509
Chon Buri	182	224	87	493
Kanchanaburi	212	198	100	510
Ratchaburi	233	237	100	570
Phetchaburi	207	289	96	592
Average	195	241	79	515
Average of Thailand	**187**	**251**	**90**	**528**

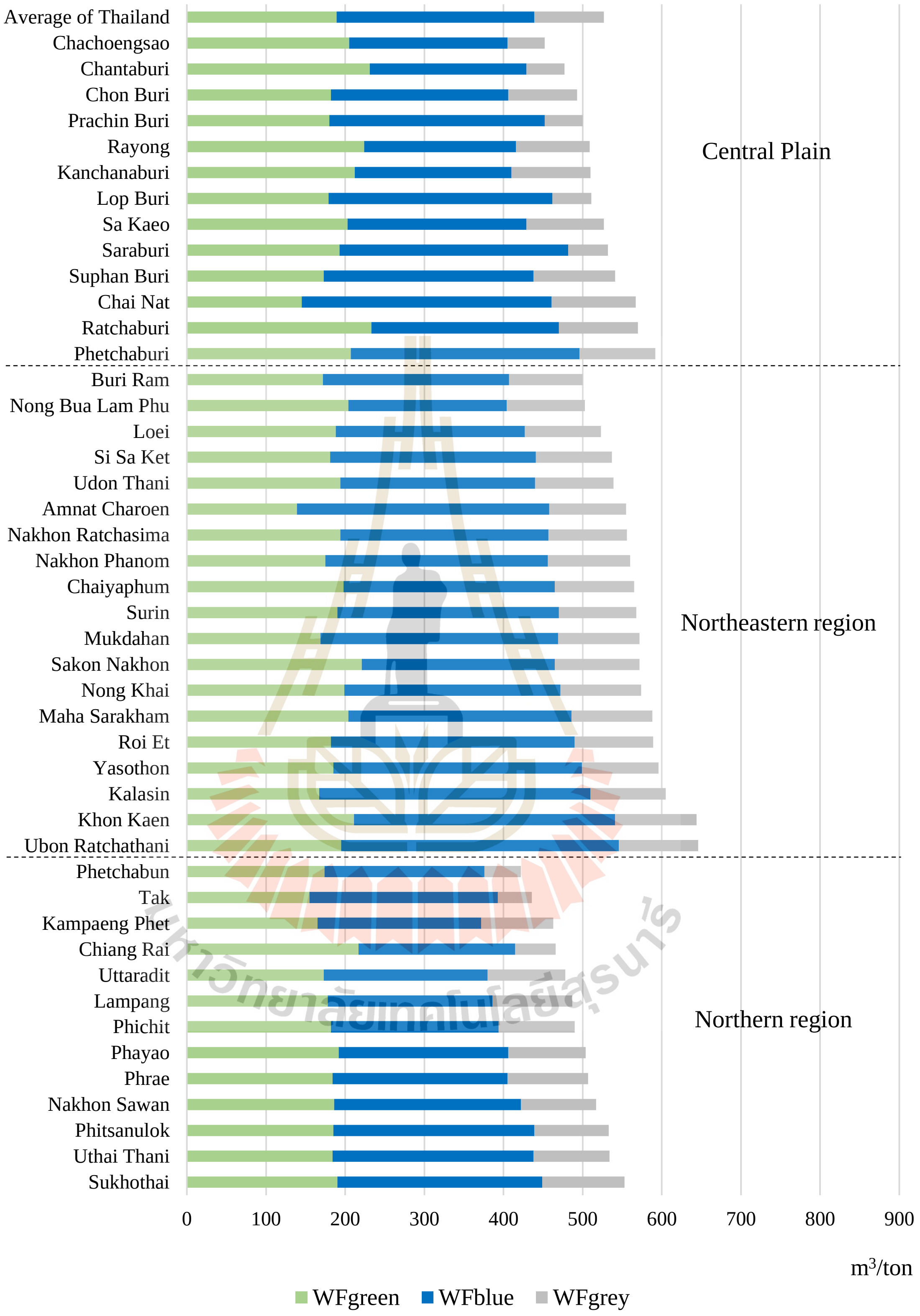


Figure 4.4 Water footprint of cassava cultivation classified into green, blue and grey components, as estimated under the irrigation schedule-option.

Few previous studies in Thailand associated with using the WF concept to calculate the amount of water use in cassava cultivation have been found. For instance, Gheewala *et al.* (2014) studied the average water consumption for food, feed and fuel crops production for the period 2009-2011. Kongboon and Sampattagul (2012) assessed the average WF of cassava cultivation in the Northern region for the period of 2008-2010. Tiewtoy *et al.* (2012) estimated the WF of cassava for ethanol production in Eastern Thailand and Gerben-Leenes *et al.* (2008) focused only on the green and blue WF of cassava cultivation in Nakhon Ratchasima province. Previous studies of the WF of cassava cultivation in other countries include the WF of cassava roots based on ethanol production in Nigeria by Adeoti (2010). Other studies, Mekonnen and Hoekstra (2011) were based on the assessment of the average WF of primary crops on a global scale from 1996-2005.

Table 4.10 shows the details of studies in Thailand with the WF_{total} in the Northern region of this study compared with a study by Kongboon and Sampattagul (2012), who have shown the same result observing that the blue component was higher than the green. In a comparison of this study with the Tiewtoy *et al.* (2012), we focused on the WF_{total} in some provinces of the Eastern region, such as Chachoengsao, Chantaburi, Rayong and Chon Buri provinces which showed a similar trend, where the green component was higher than the blue, due to the fact that both studies were conducted under the same environmental factors and the same period of time. Nevertheless, studies of Gheewala *et al.* (2014) and Gerben-Leenes *et al.* (2008) showed that the WF_{total} was quite low since it excluded the grey component. Hence, the range of the WF of cassava cultivation in Thailand was 394-528 m^3/ton. Studies of other countries show that the amount of water required to grow cassava in Nigeria is very high (up to 922 m^3/ton) because the yield was much lower than that in Thailand by almost 2 times. While a study of Mekonnen and Hoekstra (2011) revealed a global average of 564 m^3/ton.

Table 4.10 Previous studies of the Water footprint for cassava cultivation.

Authors	Study area	Water footprint of cassava (m^3/ton)			
		Green	Blue	Grey	Total
In Thailand					
This study	Average of Thailand	189	250	88	528
*Gheewala *et al.* (2014)	Average of Thailand	-	-	-	394-413
Kongboon and Sampattagul (2012)	Average of the Northern part of Thailand (13 provinces)	192	232	85	509
Tiewtoy *et al.* (2012)	Average in the Eastern of Thailand (6 provinces)	342	40	66	448
*Gerben-Leenes *et al.* (2008)	Nakhon Ratchasima province	413	42	-	455
Others					
Adeoti (2008)	Nigeria	476	516	-	992
Mekonnen and Hoekstra (2011)	Global on average	550	0	13	564

Remark: * = accounted WF without grey.

4.1.4 Water footprint of sugarcane cultivation

4.1.4.1 The green and blue crop water requirement

1) Crop water requirement

The green and blue crop water requirement of sugarcane cultivation was calculated by using the CROPWAT 8.0 program. The ET estimated under both the CWR-option and the irrigation schedule-option, it was classified into green and blue components, as displayed in Table 4.11.

Table 4.11 Crop evapotranspiration of sugarcane cultivation estimated under the CWR-option (1) and the irrigation schedule-option (2).

Provinces	Options	Crop evapotranspiration		
		ET_{green}	ET_{blue}	$ET_{c\ or\ a}$*
		(mm/growing period)		
Northern				
Lampang	1	649	374	1,023
	2	716	304	1,020
Chiang Mai	1	676	424	1,100
	2	745	353	1,098
Tak	1	644	527	1,171
	2	776	392	1,168
Kampaeng Phet	1	687	388	1,075
	2	743	329	1,072
Sukhothai	1	691	430	1,121
	2	755	364	1,119
Phrae	1	626	419	1,045
	2	689	353	1,042
Uttaradit	1	624	411	1,034
	2	683	348	1,032
Phitsanulok	1	745	480	1,225
	2	807	413	1,220
Phichit	1	683	408	1,090
	2	752	335	1,088
Nakhon Sawan	1	698	457	1,156
	2	764	388	1,153
Uthai Thani	1	752	473	1,225
	2	799	423	1,222
Phetchabun	1	639	434	1,073
	2	743	328	1,070
Northeastern				
Loei	1	700	460	1,160
	2	721	436	1,156
Nong Bua Lam Phu	1	648	418	1,066
	2	710	353	1,063
Udon Thani	1	680	477	1,157
	2	739	414	1,153
Nong Khai	1	715	482	1,198
	2	750	445	1,194
Sakon Nakhon	1	645	494	1,139
	2	704	432	1,136
Nakhon Phanom	1	600	528	1,128
	2	624	501	1,125
Mukdahan	1	602	573	1,175
	2	663	509	1,172

Table 4.11 (Continued).

Provinces	Options	Crop evapotranspiration		
		ET_{green}	ET_{blue}	$ET_{c\ or\ a}$*
		(mm/growing period)		
Yasothon	1	714	616	1,330
	2	768	558	1,326
Amnat Charoen	1	638	568	1,206
	2	392	811	1,203
Si Sa Ket	1	681	522	1,203
	2	709	490	1,200
Surin	1	708	532	1,240
	2	732	504	1,237
Buri Ram	1	675	469	1,144
	2	711	430	1,141
Maha Sarakham	1	688	571	1,259
	2	758	498	1,256
Roi Et	1	701	594	1,295
	2	733	559	1,291
Kalasin	1	680	682	1,362
	2	745	613	1,358
Khon Kaen	1	684	677	1,361
	2	751	606	1,357
Chaiyaphum	1	699	511	1,210
	2	714	493	1,206
Nakhon Ratchasima	1	688	530	1,219
	2	760	456	1,216
Central plain				
Saraburi	1	644	591	1,235
	2	903	329	1,232
Lop Buri	1	621	593	1,214
	2	902	309	1,211
Sing Buri	1	619	539	1,158
	2	760	395	1,155
Chai Nat	1	631	516	1,147
	2	744	400	1,144
Suphan Buri	1	611	515	1,126
	2	740	383	1,123
Ang Thong	1	683	618	1,301
	2	750	548	1,298
Prachin Buri	1	685	546	1,231
	2	1001	227	1,228
Chachoengsao	1	717	419	1,136
	2	800	333	1,133
Sa Kaeo	1	678	451	1,128
	2	728	398	1,125

Table 4.11 (Continued).

Provinces	Options	Crop evapotranspiration		
		ET_{green}	ET_{blue}	$ET_{c\ or\ a}$*
		(mm/growing period)		
Chantaburi	1	767	375	1,142
	2	944	195	1,139
Rayong	1	785	416	1,201
	2	861	337	1,198
Chon Buri	1	768	470	1,237
	2	634	601	1,235
Nakhon Prathom	1	641	560	1,201
	2	792	406	1,198
Kanchanaburi	1	684	398	1,081
	2	794	284	1,078
Ratchaburi	1	687	520	1,207
	2	835	368	1,203
Phetchaburi	1	644	699	1,343
	2	792	547	1,339
Prachuap Khiri Khan	1	714	459	1,172
	2	839	331	1,169

Remark * = ET_c was the ET estimated under CWR-option (1), ET_a was the ET estimated under the irrigation schedule-option (2).

2) The evaporation of crop water use and water footprint.

The details from Table 4.12 can be summarized by stating that a comparison of the amount of water use between green and blue with both the CWR-option and the irrigation schedule-option were different. The Northeastern region has the largest average CWU_{eva} and WF_{eva}, followed by the Central Plain and the Northern region, respectively. The amount of green water was much higher than the blue, especially when estimated under the irrigation schedule-option: it was found to be almost 2 times higher. This may be because the entire crop cycle was cultivated with an abundance of soil moisture content and/or effective rainfall. When we determined the sugarcane's planting date is on 1st May, the development and middle crop growing stage (these stages required very high water use) will be in June to September which is the same duration as the wet season that has intensive rainfall. If the crop could receive an increase of green water, then only a small amount of blue water would be required.

With regard to the Northern region, it was found the average CWU_{green}, CWU_{blue} and CWU_{eva} estimated under the CWR-option was 6,761, 4,354 and 11,115 m^3/ha, respectively, while under the irrigation schedule-option it was 7,477, 3,607 and 11,084 m^3/ha, respectively. On the other hand, the average WF_{green}, WF_{blue} and WF_{eva} estimated under the CWR-option was 97, 62 and 159 m^3/ton, whereas under the irrigation schedule-option it was 107, 51 and 158 m^3/ton. The three largest values of CWU_{eva} and WF_{eva} under the irrigation schedule-option were observed at Phitsanulok, Uthai Thani, and Tak provinces, respectively.

For the Northeastern region, the CWU_{green}, CWU_{blue} and CWU_{eva} were estimated under the CWR-option at 6,749, 5,391 and 12,140 m^3/ha, respectively, while under the irrigation schedule-option it was 7,046, 5,059 and 12,105 m^3/ha, respectively. The average values of WF_{green}, WF_{blue} and WF_{eva} under the CWR-option were at 96, 77 and 173 m^3/ton, respectively, while under the irrigation schedule-option it was 100, 72, 172 m^3/ton, respectively. Finally, the three largest values for CWU_{eva} and WF_{eva} under the irrigation schedule-option were found at Kalasin, Khon Kaen and Yasothon province, respectively.

For the Central Plain, CWU_{green}, CWU_{blue} and CWU_{eva} were estimated under the CWR-option at 6,810, 5,108 and 11,918 m^3/ha, respectively, while under the irrigation schedule-option it was 8,127, 3,760 and 11,887 m^3/ha, respectively. On the other hand, the average for WF_{green}, WF_{blue} and WF_{eva} under the CWR-option was 94, 70 and 164 m^3/ton, while under the irrigation schedule-option it was 112, 52 and 164 m^3/ton. The three highest values of CWU_{eva} and WF_{eva} estimated under the irrigation schedule-option were at Prachin Buri, Ang Thong and Chon Buri provinces, respectively.

Table 4.12 The evaporation of crop water use and water footprint of sugarcane cultivation estimated under the CWR-option (1) and the irrigation schedule-option (2).

Provinces	Opt.*	CWU_{green}	CWU_{blue}	CWU_{eva}	WF_{green}	WF_{blue}	WF_{eva}
		m^3/ha			m^3/ton		
Northern							
Lampang	1	6,488	3,739	10,227	132	76	208
	2	7,158	3,040	10,198	146	62	208
Chiang Mai	1	6,757	4,244	11,001	119	75	194
	2	7,449	3,530	10,979	132	62	194
Tak	1	6,438	5,274	11,712	105	86	191
	2	7,757	3,918	11,675	127	64	191
Kampaeng Phet	1	6,868	3,878	10,746	85	48	133
	2	7,433	3,287	10,720	92	41	133
Sukhothai	1	6,912	4,302	11,214	97	60	157
	2	7,549	3,636	11,185	106	51	157
Phrae	1	6,260	4,190	10,450	92	62	154
	2	6,892	3,529	10,421	102	52	154
Uttaradit	1	6,238	4,105	10,343	87	57	144
	2	6,834	3,483	10,317	95	49	144
Phitsanulok	1	7,454	4,795	12,249	104	67	171
	2	8,070	4,125	12,195	113	58	171
Phichit	1	6,828	4,076	10,904	98	58	156
	2	7,521	3,354	10,875	108	48	156
Nakhon Sawan	1	6,984	4,574	11,558	85	56	141
	2	7,642	3,883	11,525	93	47	140
Uthai Thani	1	7,517	4,731	12,248	98	62	160
	2	7,990	4,227	12,217	104	55	159
Phetchabun	1	6,392	4,339	10,731	77	52	129
	2	7,425	3,277	10,702	89	39	128
Average	1	6,761	4,354	11,115	97	62	159
	2	7,477	3,607	11,084	107	51	158
Northeastern							
Loei	1	7,000	4,601	11,601	105	69	174
	2	7,209	4,355	11,564	108	65	173
Nong Bua Lam Phu	1	6,483	4,180	10,663	96	62	158
	2	7,103	3,528	10,631	105	52	157
Udon Thani	1	6,799	4,768	11,567	102	71	173
	2	7,388	4,144	11,532	111	62	173

Table 4.12 (Continued).

Provinces	Opt.*	CWU_{green}	CWU_{blue}	CWU_{eva}	WF_{green}	WF_{blue}	WF_{eva}
			m^3/ha			m^3/ton	
Nong Khai	1	7,151	4,824	11,975	106	71	177
	2	7,496	4,445	11,941	111	66	177
Sakon Nakhon	1	6,450	4,943	11,393	96	74	170
	2	7,039	4,322	11,361	105	65	170
Nakhon Phanom	1	6,004	5,278	11,282	87	76	163
	2	6,238	5,011	11,249	90	73	163
Mukdahan	1	6,024	5,728	11,752	85	80	165
	2	6,626	5,092	11,718	93	72	165
Yasothon	1	7,137	6,164	13,301	101	88	189
	2	7,682	5,578	13,260	109	79	188
Amnat Charoen	1	6,381	5,682	12,063	91	81	172
	2	3,920	8,109	12,029	56	115	171
Si Sa Ket	1	6,812	5,218	12,030	102	78	180
	2	7,094	4,903	11,997	106	73	179
Surin	1	7,079	5,318	12,397	104	78	182
	2	7,324	5,041	12,365	108	74	182
Buri Ram	1	6,748	4,692	11,440	95	66	161
	2	7,105	4,302	11,407	100	61	161
Maha Sarakham	1	6,884	5,705	12,589	103	85	188
	2	7,575	4,980	12,555	113	74	187
Roi Et	1	7,011	5,936	12,947	97	82	179
	2	7,328	5,585	12,913	101	77	178
Kalasin	1	6,803	6,815	13,618	94	94	188
	2	7,446	6,131	13,577	102	84	186
Khon Kaen	1	6,836	6,774	13,610	90	89	179
	2	7,513	6,056	13,569	99	80	179
Chaiyaphum	1	6,987	5,110	12,097	99	73	172
	2	7,136	4,928	12,064	102	70	172
Nakhon Ratchasima	1	6,884	5,304	12,188	100	77	177
	2	7,597	4,558	12,155	111	67	178
Average	1	6,749	5,391	12,140	96	77	173
	2	7,046	5,059	12,105	100	72	172
Central Plain							
Saraburi	1	6,443	5,909	12,352	91	83	174
	2	9,032	3,286	12,318	128	46	174
Lop Buri	1	6,209	5,934	12,143	88	84	172
	2	9,017	3,094	12,111	127	44	171
Sing Buri	1	6,189	5,389	11,578	82	72	154
	2	7,595	3,954	11,549	101	53	154
Chai Nat	1	6,310	5,156	11,466	82	67	149
	2	4,001	7,437	11,438	97	52	149
Suphan Buri	1	6,110	5,148	11,258	74	62	136
	2	7,398	3,832	11,230	89	46	135

Table 4.12 (Continued).

Provinces	Opt.*	CWU_{green}	CWU_{blue}	CWU_{eva}	WF_{green}	WF_{blue}	WF_{eva}
			m^3/ha			m^3/ton	
Ang Thong	1	6,831	6,183	13,014	93	84	177
	2	7,497	5,480	12,977	102	75	177
Prachin Buri	1	6,848	5,458	12,306	106	84	190
	2	10,011	2,267	12,278	155	35	190
Chachoengsao	1	7,169	4,191	11,360	116	68	184
	2	8,000	3,331	11,331	130	54	184
Sa Kaeo	1	6,775	4,508	11,283	106	70	176
	2	7,278	3,976	11,254	114	62	176
Chantaburi	1	7,669	3,751	11,420	122	60	182
	2	9,436	1,954	11,390	150	31	181
Rayong	1	7,851	4,162	12,013	124	66	190
	2	8,610	3,374	11,984	136	53	189
Chon Buri	1	7,675	4,698	12,373	119	73	192
	2	6,337	6,008	12,345	98	93	191
Nakhon Prathom	1	6,407	5,600	12,007	82	72	154
	2	7,917	4,059	11,976	102	52	154
Kanchanaburi	1	6,838	3,976	10,814	93	54	147
	2	7,944	2,840	10,784	108	38	146
Ratchaburi	1	6,867	5,199	12,066	99	75	174
	2	8,348	3,684	12,032	120	53	173
Phetchaburi	1	6,442	6,987	13,429	102	110	212
	2	7,916	5,474	13,390	125	86	211
Prachuap Khiri Khan	1	7,139	4,585	11,724	115	74	189
	2	8,385	3,305	11,690	135	53	188
Average	1	6,810	5,108	11,918	94	70	164
	2	8,127	3,760	11,887	112	52	164
Average of Thailand	**1**	**6,774**	**5,024**	**11,798**	**92**	**69**	**161**
	2	**7,547**	**4,219**	**11,766**	**103**	**58**	**161**

Remark * = options.

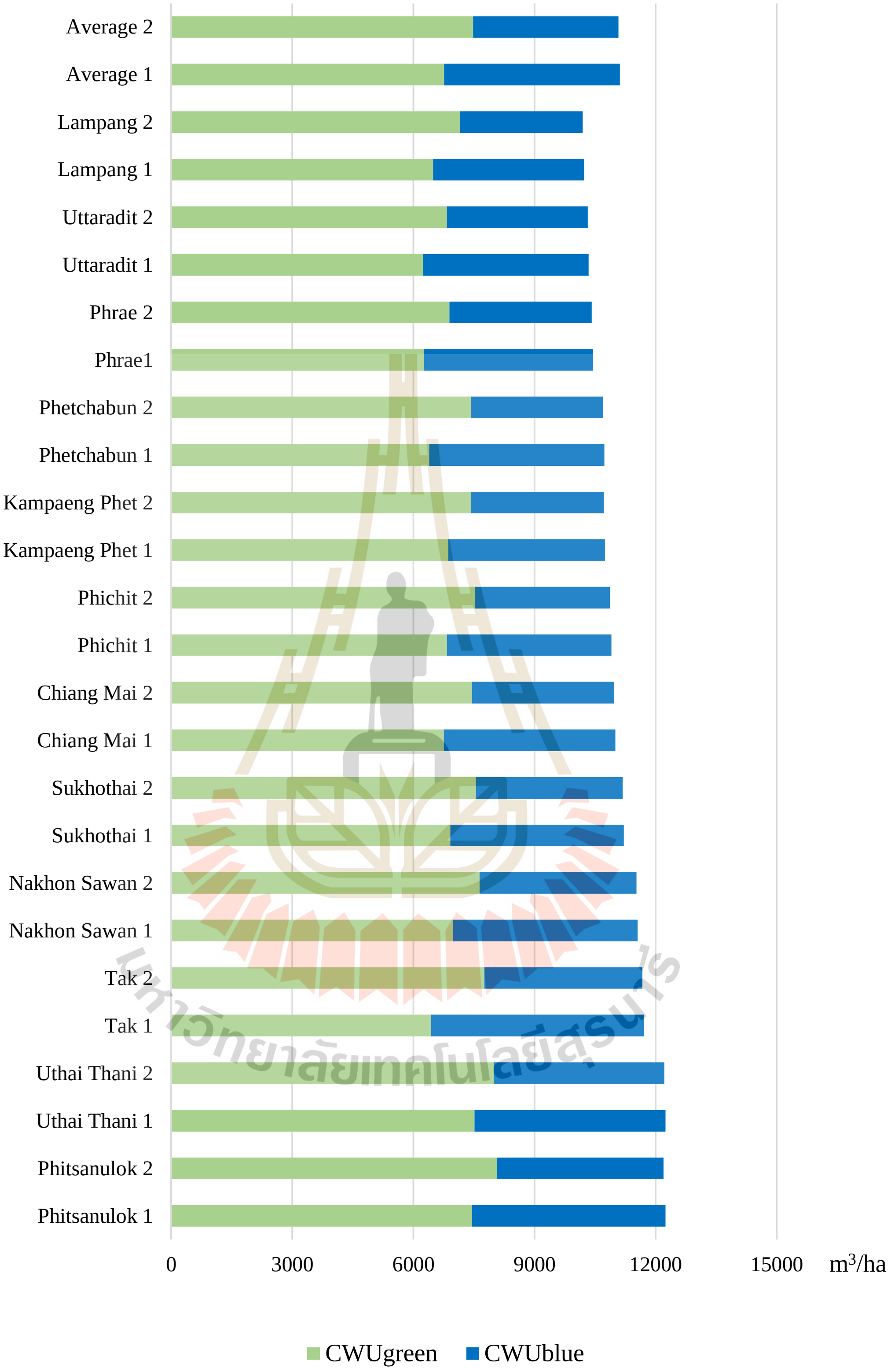


Figure 4.5 The CWU of sugarcane cultivation in the Northern region estimated under the CWR-option (1) and the irrigation schedule-option (2).

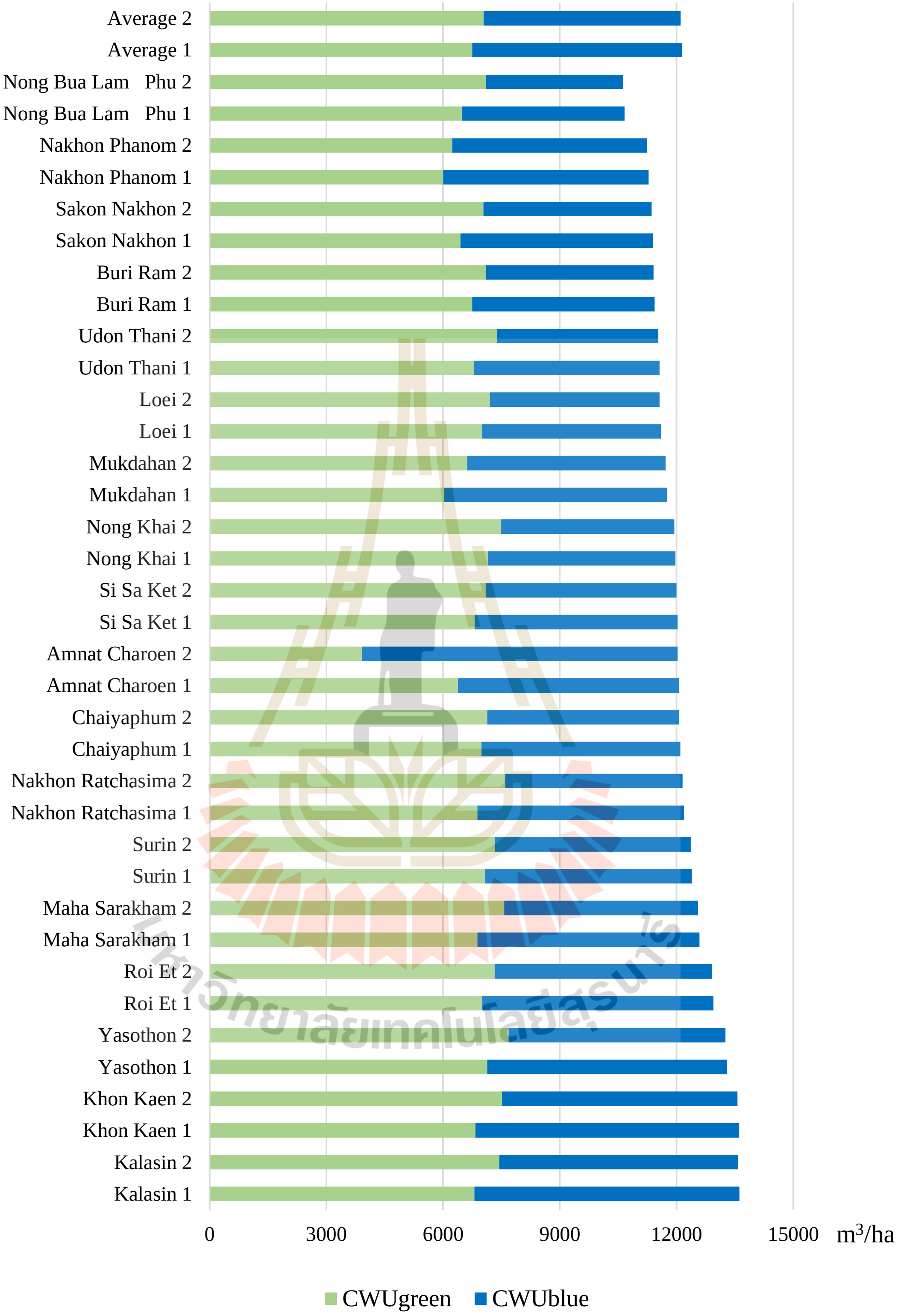


Figure 4.6 The CWU of sugarcane cultivation in the Northeastern region estimated under the CWR-option (1) and the irrigation schedule-option (2).

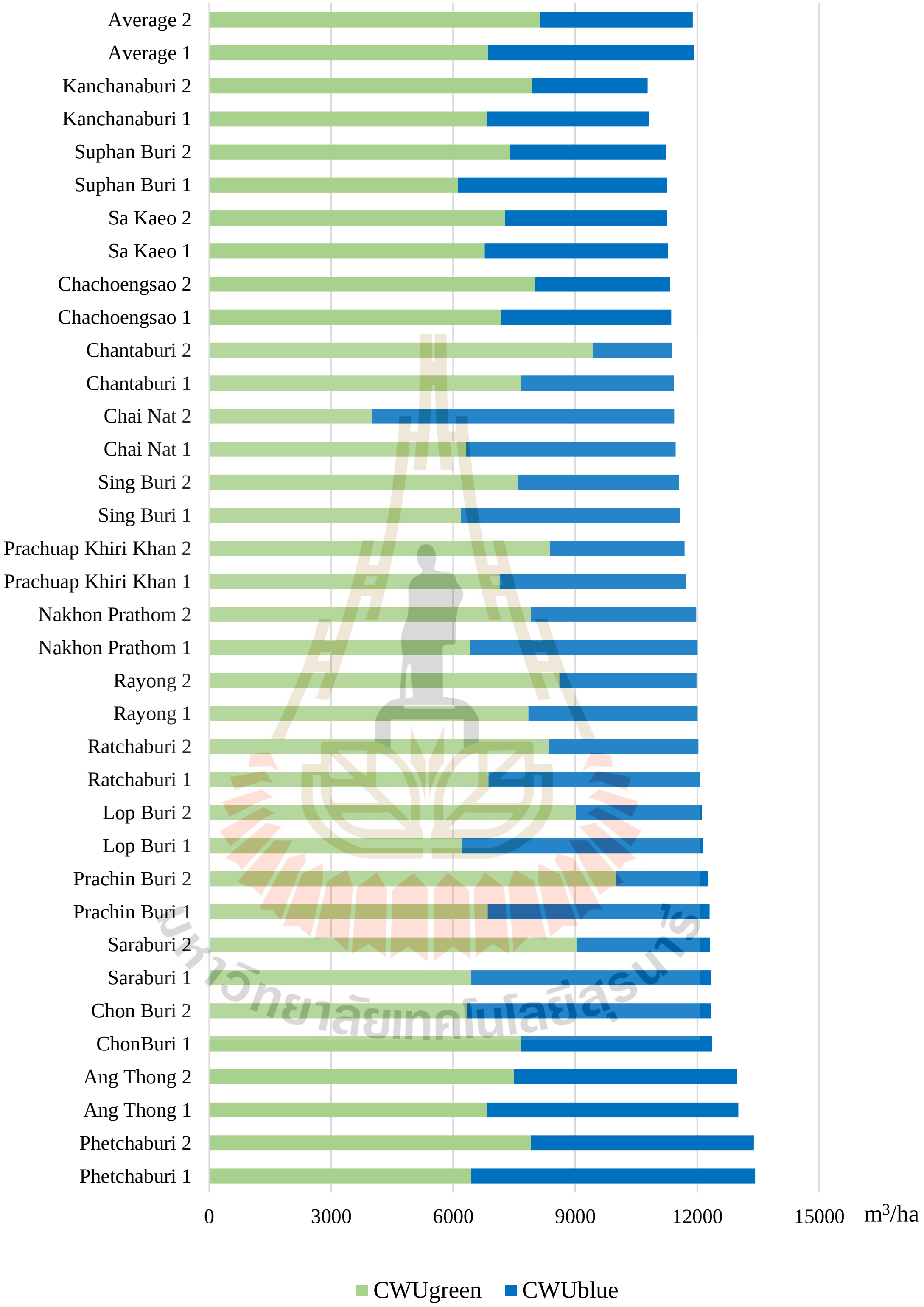


Figure 4.7 The CWU of sugarcane cultivation in the Central Plain estimated under the CWR-option (1) and the irrigation schedule-option (2).

4.1.4.2 Grey water footprint

The WF_{grey} of sugarcane cultivation was calculated by a similar equation as used for cassava cultivation. According to the details of fertilizer application in the fields as shown in Table 4.2, 10% of N-fertilizer was applied to the crop and the approximate amount of chemicals reaching the water bodies was used to calculate the grey component. The results from Table 4.13 show that the Central Plain had an average WF_{grey} which was higher than the Northern and Northeastern regions, which was 36, 35 and 33 m^3/ton, respectively. Tak, Chachoengsao and Chantaburi provinces had the three highest amounts of WF_{grey}, which is the result of the clay soil that required a very much amount of N-fertilizer application for the crop.

Table 4.13 Quantities of nitrogen fertilizer applied to the field and grey water footprint of sugarcane cultivation.

Provinces	N-fertilizer (ton/crop cycle)	Grey WF (m^3/ton)
Northern		
Lampang	565	46
Chiang Mai	46	40
Tak	215	49
Kampaeng Phet	7,571	28
Sukhothai	3,047	32
Phrae	37	33
Uttaradit	1,676	32
Phitsanulok	2,410	32
Phichit	874	32
Nakhon Sawan	10,378	28
Uthai Thani	4,294	29
Phetchabun	6,327	36
Average	-	35
Northeastern		
Loei	1,520	34
Nong Bua Lam Phu	1,233	33
Udon Thani	6,652	34

Table 4.13 (Continued).

Provinces	N-fertilizer (ton/crop cycle)	Grey WF (m^3/ton)
Nong Khai	127	33
Sakon Nakhon	474	34
Nakhon Phanom	110	33
Mukdahan	1,752	32
Yasothon	224	32
Amnat Charoen	164	32
Si Sa Ket	98	34
Surin	2,956	33
Buri Ram	2,234	32
Maha Sarakham	1,161	34
Roi Et	628	31
Kalasin	4,937	31
Khon Kaen	8,980	30
Chaiyaphum	6,468	32
Nakhon Ratchasima	10,296	33
Average	-	33
Central Plain		
Saraburi	3,644	42
Lop Buri	7,947	42
Sing Buri	823	30
Chai Nat	969	29
Suphan Buri	7,693	27
Ang Thong	294	31
Prachin Buri	210	46
Chachoengsao	1,033	49
Sa Kaeo	3,711	35
Chantaburi	404	48
Rayong	421	36
Chon Buri	1,898	35
Nakhon Prathom	1,387	29
Kanchanaburi	11,893	31
Ratchaburi	3,266	33
Phetchaburi	441	36
Prachuap Khiri Khan	596	36
Average	-	36
Average of Thailand	**-**	**34**

4.1.4.3 Total water footprint

To assess the WF_{total} of sugarcane cultivation in three regions of Thailand, namely, the Northern, the Northeastern and the Central Plain during the period of 2008-2013, only the irrigation schedule-option was used. The WF_{total} was the summation of the green, blue (data from Table 4.12) and grey (data from Table 4.13) WF_S, as shown in Table 4.14.

The results showed that the average WF_{total} in the Northeastern region were the highest, followed by the Central Plain the and Northern regions, which were 205 m^3/ton (57, 26 and 17% of green, blue and grey), 200 m^3/ton (49, 35 and 16% of green, blue and grey) and 193 m^3/ton (55, 27 and 18% of green, blue and grey), respectively. However, the average amount for Thailand was 195 m^3/ton, consisting of green (103 m^3/ton), blue (58 m^3/ton) and grey (34 m^3/ton) components.

On the other hand, in the Northern region in 12 provinces, it was found that the three largest amounts of WF_{total} in decreasing order were Lampang (254 m^3/ton), Tak (240 m^3/ton) and Chiang Mai (234 m^3/ton). In 18 provinces of the Northeastern region, the three largest WF_{total} were Maha Sarakham (221 m^3/ton), Yasothon (220 m^3/ton) and Kalasin (217 m^3/ton). In addition, for the Central Plain out of 17 provinces, the three largest of WF_{total} were Phetchaburi (247 m^3/ton), Prachin Buri (236 m^3/ton) and Chachoengsao (233 m^3/ton).

The green WF of sugarcane cultivation consumed higher than 2 times the blue amounts and 3 times the grey amounts. Nevertheless, only Amnat Charoen province was found to have a WF_{green} less than WF_{blue}, possibly because Amnat Charoen province received only a very low rainfall, and the sandy soil in which the crop was cultivated affected the initial available soil moisture value which was low.

When the amount of rainfall was very lowefficiency, greater amounts of irrigation water had to be distributed on the crops to compensate for the low rainfall.

Table 4.14 Total water footprint of sugarcane cultivation estimated under the irrigation schedule-option.

Provinces	WF of sugarcane (m^3/ton)			
	Green	Blue	Grey	Total
Northern				
Lampang	146	62	46	254
Chiang Mai	132	62	40	234
Tak	127	64	49	240
Kampaeng Phet	92	41	28	161
Sukhothai	106	51	32	189
Phrae	102	52	33	187
Uttaradit	95	49	32	176
Phitsanulok	113	58	32	203
Phichit	108	48	32	188
Nakhon Sawan	93	47	28	168
Uthai Thani	104	55	29	188
Phetchabun	89	39	36	164
Average	107	51	35	193
Northeastern				
Loei	108	65	34	207
Nong Bua Lam Phu	105	52	33	190
Udon Thani	111	62	34	207
Nong Khai	111	66	33	210
Sakon Nakhon	105	65	34	204
Nakhon Phanom	90	73	33	196
Mukdahan	93	72	32	197
Yasothon	109	79	32	220
Amnat Charoen	56	115	32	203
Si Sa Ket	106	73	34	213
Surin	108	74	33	215
Buri Ram	100	61	32	193
Maha Sarakham	113	74	34	221
Roi Et	101	77	31	209
Kalasin	102	84	31	217
Khon Kaen	99	80	30	209
Chaiyaphum	102	70	32	204
Nakhon Ratchasima	111	67	33	211
Average	100	72	33	205
Central Plain				
Saraburi	128	46	42	216
Lop Buri	127	44	42	213

Table 4.14 (Continued).

Provinces	WF of sugarcane (m^3/ton)			
	Green	Blue	Grey	Total
Sing Buri	101	53	30	184
Chai Nat	97	52	29	178
Suphan Buri	89	46	27	162
Ang Thong	102	75	31	208
Prachin Buri	155	35	46	236
Chachoengsao	130	54	49	233
Sa Kaeo	114	62	35	211
Chantaburi	150	31	48	229
Rayong	136	53	36	225
Chon Buri	98	93	35	226
Nakhon Prathom	102	52	29	183
Kanchanaburi	108	38	31	177
Ratchaburi	120	53	33	206
Phetchaburi	125	86	36	247
Prachuap Khiri Khan	135	53	36	224
Average	112	52	36	200
Average of Thailand	**103**	**58**	**34**	**195**

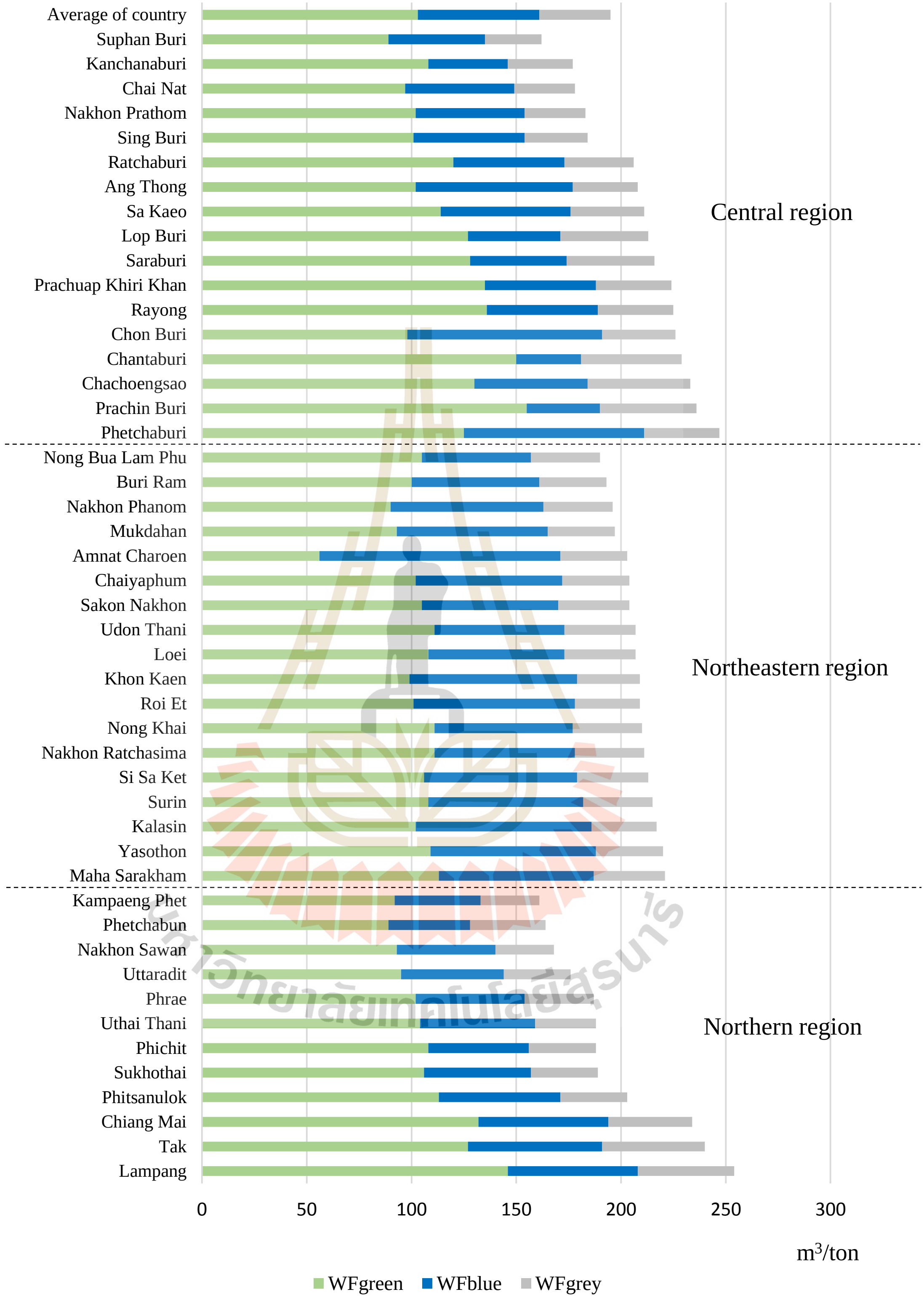


Figure 4.8 Water footprint of sugarcane cultivation classified into green, blue and grey components, estimated under the irrigation schedule-option.

The literature review associated with the WF of sugarcane cultivation in previous Thai studies showed that there were not many studies or many authors who conducted similar research on cassava cultivation. The authors who studied both WF of sugarcane and cassava were Gheewala *et al.* (2014), Tiewtoy *et al*. (2012), Kongboon and Sampattagul (2012) and Gerben-Leenes *et al.* (2008). In addition, Ngamsomrit (2013) also conducted research on the assessment of WF in the sugar industry in order to evaluate water use management and Chooyok *et al.* (2013) by means of assessing the WF of ethanol production based on molasses in Kanchanaburi and Supanburi Provinces of Thailand.

Previous studies about the WF of sugarcane cultivation from other countries, were conducted by Scholten (2009), who assessed the WF of sugar and sugar-based ethanol in part of unprocessed sugarcane for the main producing countries (including Thailand). In addition, a study by Mekonnen and Hoekstra (2011), reported the average WF of primary crops on a global scale during 1996-2005. The results of WF of sugarcane cultivation in Thailand and other countries based on previous studies are shown in Table 4.15.

These previous studies of Thailand classified the WF into three components: green, blue and grey, except for the study of Gheewala *et al.* (2004) and Gerben-Leenes *et al.* (2008) who only took into account the green and blue components. The WF_{total} of sugarcane cultivation in Thailand varies between 150-301 m^3/ton, including the results of this study which are also in this range. A comparison of the components of its WF showed that the green component was higher than the blue. For the results of WF of sugarcane cultivation from other countries, Scholten (2009) showed that the volume of water use for unprocessed sugarcane in the 21 main producing countries varies between 143-544 m^3/ton in Peru, Egypt, Colombia and Guatemala which have high yields resulting in low WFs, while in Cuba and Pakistan very low yields were reported resulting in a very large WF. Peru, Egypt, Australia, India and Pakistan have a large blue component and are completely or highly dependent on irrigation. However, the average volume of water use in Thailand and other countries has a different ratio between green and blue components that depends on the environmental factors and agricultural practices in each country.

Table 4.15 Previous studies of the water footprint for sugarcane cultivation.

Authors	Study area	Water footprint of sugarcane (m^3/ton)			
		Green	Blue	Grey	Total
In Thailand					
In this study	Average of Thailand	110	60	35	205
*Gheewala *et al.* (2014)	Average of Thailand	-	-	-	150-174
Ngamsomrit (2013)	Phitsanulok province	111	76	26	213
	Sukhothai province	115	76	26	217
	Uttaradit province	97	82	24	203
Chooyok *et al.* (2013)	Kanchanaburi province	139	34	45	218
	Supanburi province	134	19	65	218
Kongboon and Sampattagul (2012)	Average of Northern part of Thailand	90	87	25	202
Tiewtoy *et al.* (2012)	Average of Eastern of Thailand	161	11	19	191
Scholten (2009)	Average of Thailand	152	132	18	301
*Gerben-Leenes *et al.* (2008)	Nakhon Ratchasima province	128	148	-	276
Other countries					
Mekonnen and Hoekstra (2011)	Global on average	139	57	13	210
Scholten (2009)	Peru	0	134	8	143
	Ethiopia	55	94	10	159
	Egypt	7	156	7	163
	Colombia	125	29	11	166
	Guatemala	118	45	11	174

Table 4.15 (Continued).

Authors	Study area	Water footprint of sugarcane (m^3/ton)			
		Green	Blue	Grey	Total
	China	130	47	22	199
	Brazil	115	87	8	209
	Philippines	160	41	12	213
	Argentina	65	137	12	215
	Morocco	56	147	14	218
	USA	122	102	13	237
	Indonesia	184	46	13	240
	Australia	65	152	27	243
	India	85	156	15	256
	Venezuela	96	157	22	275
	Belize	206	51	20	277
	Viet Nam	160	98	20	278
	South Africa	100	187	19	306
	Pakistan	29	402	26	457
	Cuba	310	214	20	544
	Global on average	109	121	14	243

Remark: * = accounted WF without grey.

4.1.5 A comparison of the volume of water use between cassava and sugarcane cultivation

In order to present the volume of water use of the two major crops of cassava and sugarcane during the period of 2008-2013 estimated under the irrigation schedule-option, the CWU of both cassava and sugarcane cultivation was divided into two components, green and blue, and it was estimated for three regions: the Northern, Northeastern and Central Plain of Thailand in order to obtain the appropriate amount of water use to produce these major corps throughout the entire country. This was done in order to obtain a better understanding of the water consumed by these different crops.

Table 4.16 shows the respective water consumption for cassava and sugarcane cultivation in Thailand.

Table 4.16 Crop water use of cassava and sugarcane cultivation estimated under the irrigation schedule-option.

Regions	CWU of cassava (m^3/ha)			CWU of sugarcane (m^3/ha)		
	Green	Blue	Eva*	Green	Blue	Eva*
Northern	3,773	4,659	8,432	7,477	3,607	11,084
Northeastern	3,777	5,654	9,431	7,046	5,059	12,105
Central Plain	4,079	5,036	9,115	8,127	3,760	11,887
Average of Thailand	**3,863**	**5,188**	**9,051**	**7,547**	**4,219**	**11,766**

Remark: * = Evaporation.

Table 4.16 shows a comparison of the crop water use for cassava and sugarcane cultivation in Thailand, estimated under the irrigation schedule-option. The results are displayed in cubic meters per hectare over the growing period of the crops. Sugarcane plantations consumed an average CWU_{eva} in the whole country which was higher than cassava plantation, and sugarcane plantations consumed around 11,766 m^3/ha (3,863 and 5,188 m^3/ha of green and blue), while cassava plantations consumed 9,051 m^3/ha (7,547 and 4,219 m^3/ha of green and blue).

Although the cropping cycle of sugarcane is short at around 10 months (320 days), whereas the cropping cycle of cassava extends over a whole year (360 days), it was found that the sugarcane plantations consumed more water than the cassava plantations. This can be explained in relation to the following equation (3.1), where the ET accumulation is obtained by multiplying K_c and ET_o over the growing period, with the K_c of sugarcane in the middle growing stage at the highest level (K_c; 1.25) during the long growing period (180 days), which results in high water consumption. In contrast the cassava plantation has the longest growing period in the initial growing stage (150 days) that requires the lowest K_c value (K_c; 0.3), which results in low water consumption. This was the reason why the sugarcane plantations required a higher volume of water use during the growing period than the cassava plantations.

To estimate the WF of cassava and sugarcane cultivation, the CWU is divided by the crop yields in the different areas of Thailand as shown in Table 4.17.

Table 4.17 Water footprint of cassava and sugarcane cultivation estimated under the irrigation schedule-option.

Regions	WF of cassava (m^3/ton)					WF of sugarcane (m^3/ton)				
	Green	Blue	Grey	Eva	Total	Green	Blue	Grey	Eva	Total
Northern	176	217	86	393	479	107	51	35	158	193
Northeastern	187	280	99	467	566	100	72	33	172	205
Central Plain	195	241	79	436	515	112	52	36	164	200
Average of Thailand	**187**	**251**	**90**	**438**	**528**	**103**	**58**	**34**	**161**	**195**

The results in Table 4.17 show the average WF_{total} in cubic meters per ton of cassava and sugarcane cultivation by region. Crops with a high production generally have a smaller WF than crops with a low production. Hence, the WF_{total} of sugarcane cultivation is lower than that for cassava cultivation, because sugarcane has a high production when compared with cassava. Large amounts of water use are necessary for cassava and sugarcane cultivation, for instance, using the average based on this study, it was observed that the required CWU_{eva} of cassava (8,992 m^3/ha) was lower than for sugarcane (11,692 m^3/ha), but the WF_{eva} shows the opposite trend, as cassava (438 m^3/ton) was higher than sugarcane (161 m^3/ton). This can be explained by the fact that both the cassava and sugarcane have different yields (the cassava yield was around 21 ton/ha, while the sugarcane yield was around 70 ton/ha). Thus, we can conclude that the large amount of yields is influenced by agricultural management rather than by the agro-climate in which the crop was grown.

In the case of sugarcane cultivation, a higher green WF is required than for blue WF which is the result of good practice in water appropriation. A suitable sugarcane planting date was determined to begin in May (initial rainfall) because the planting date related to the agro-climatic pattern that matches with good cropping practices throughout the growing period by farmers. In the case of cassava cultivation, a higher blue WF was required than for green. The planting date for cassava was also determined to begin in May. Because of its crop characteristics, cassava requires more time for crop planting in the initial growing stage (150 days). If the planting date for cassava can be changed to February, the development and middle crop growing stage (high water requirement) will be in the rainy season in June to September, in order for the crop to consume a greater amount of green water.

In other words, the total WF for both cassava and sugarcane cultivation varies according to the different regions, possibly because the factors in a distinct area were very significant such as climate and soil data which were collected by different investigators that affect the different size of the WF.

Nevertheless, the climatic data should be averaged over 30 years to obtain a precise calculation of average ET_o, which can help to establish the suitability of a cropping pattern and the amount of irrigated water associated with the crop and soil characteristics. This should help to sustain and manage the water resources of the cassava and sugarcane plantations.

4.2 Water footprint of cassava starch and refined sugar

4.2.1 Product and value fractions

Cassava and sugarcane crops were processed into products (cassava processed into starch and sugarcane processed into refined sugar) with the result that the weight of the remaining product is smaller than original product. Calculating the WF of crop products from the start as crop cultivation transform to the final production in the industrial sector is calculated by following the equation (3.16) as shown in Chapter III. The product fraction is defined as the ratio of the weight of the resulting product to the weight of the original product. While the value fraction for a processed product is defined as the ratio of the market value of the output product to the aggregated market value of all the output products obtained from the input products. The product and value fractions obtained from the literature review for cassava starch and refined sugar are shown in Tables 4.18 and 4.19.

Table 4.18 Product fractions of cassava starch and sugar.

Product fractions	References
Cassava starch	
25%	Rao (1997)
<25%	FAO (2003)
25%	Rojanaridpiched *et al.* (2002)
25-35%	Wang (2002)
24-28%	Jie *et al.* (2002)
20%	1st factory of this study
25%	2nd factory of this study
27%	3rd factory of this study
21%	Khongsiri (2009)
24%	Chavalparit and Ongwandee (2009)
24%	Jakrawatana *et al.* (2015)
27%	Usubharatana and Phungrassami (2015)
sugar	
12.5%	Rao (1997)
<15%	FAO (2003)

Table 4.18 (Continued).

Product fractions	References
14%	Gerbens-Leenes and Hoekstra (2009)
14%	Scholten (2009)
14%	Ercin *et al*. (2011)
Refined sugar	
<14%	FAO (2003)
9.2%	Factory of this study
3.2%	Witayapairot (2010)
1.8%	Department of Industrial Works (2013)

Table 4.19 Value fractions of cassava starch and sugar.

Value fractions	Country	References
Cassava starch		
0.87	Thailand	Khongsiri (2009)
sugar		
0.76	Brazil	Scholten (2009)
0.87	India	
0.90	China	
0.83	Thailand	
0.90	Australia	
0.88	USA	
0.87	Average of the main sugarcane producing countries	Gerbens-Leenes and Hoekstra (2009)

4.2.2 Water footprint of cassava starch

4.2.2.1 Processing and water mass flow balance

To estimate the WF of cassava starch processing, three cassava starch factories in Nakhon Ratchasima province were selected as case studies to collect data concerning water consumption and wastewater generation. Cassava starch processing is similar among the factories of Thailand, but there may be differences in the techniques and machines used in each production stage of the processing industries (Chavalparit and Ongwandee, 2009). In this study, the three cassava starch factories can produce native starch per day at 250 tons, 300 tons and 500 tons, respectively. The amount of water use in processing will be applied to the water mass flow balance based on one ton of cassava starch as shown in Figures 4.9, 4.10 and 4.11. The water use in three cassava factories varied between 39.2-6.1 m^3/ton. According to the studies of Chavalparit and Ongwandee (2009) and Jakrawatana *et al*. (2015), the water use in cassava processing is approximately 18±11.3 and 18±11 m$^{3/}$ton, respectively, which depends on whether the water is recycled or not.

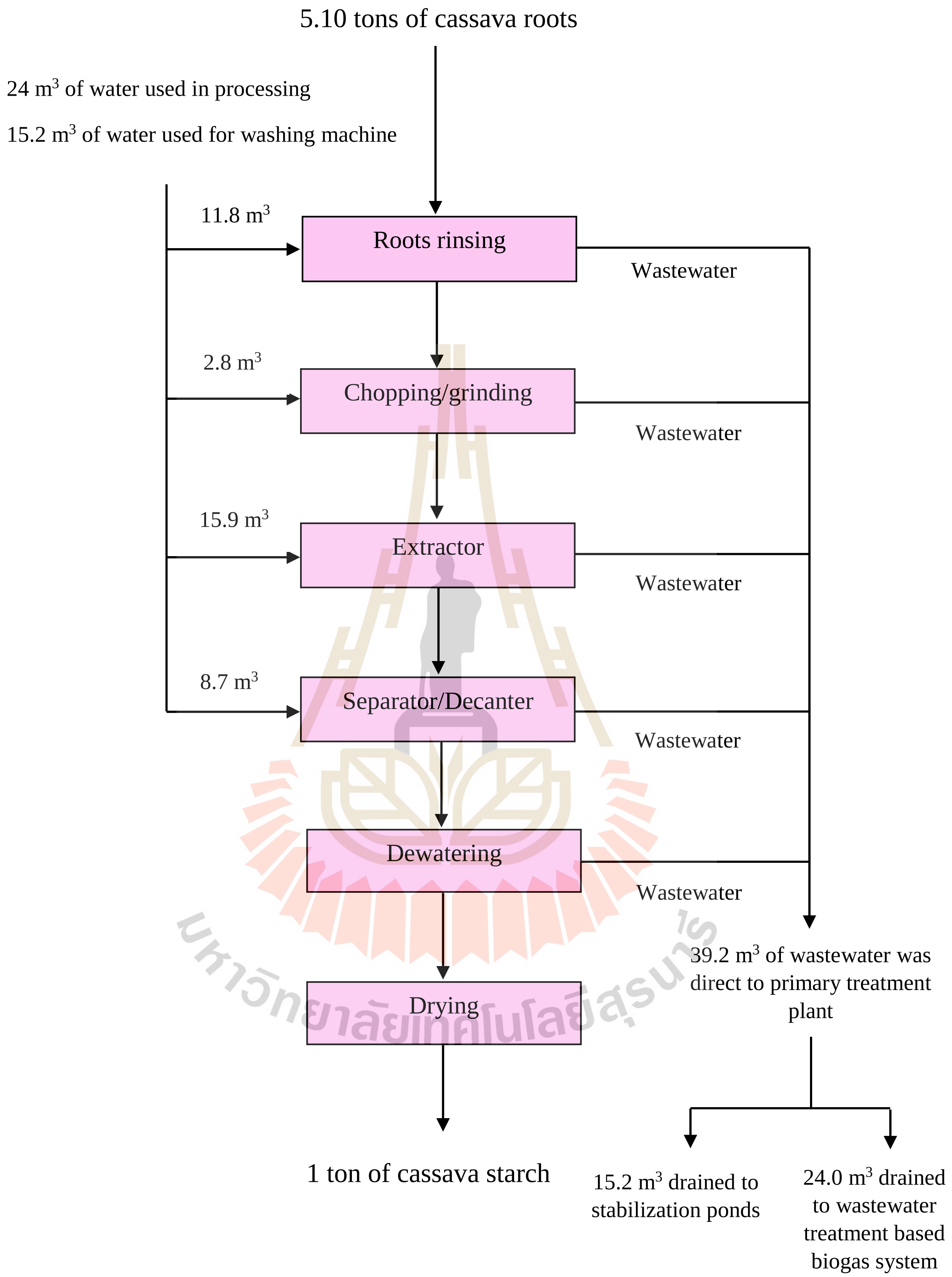


Figure 4.9 Process steps and water mass flow balance for the 1st cassava starch factory.

Water consumption per one ton of cassava starch for the1st factory did not reuse and recycle water from the waste of the process lines. The total water consumption during the processing required 39.2 m^3 that was separated in each step of the processing that was equal to 11.8 m^3 for roots rinsing, 2.8 m^3 for chopping/grinding, 15.9 m^3 for extractor and 8.7 m^3 for the separator. The total water consumption used was for both processing (24.0 m^3) and the washing machine (15.2 m^3). Furthermore, the wastewater from processing was distributed into the primary treatment and then drained to the wastewater treatment system based on a biogas system, while the wastewater from the washing machine was drained directly into the primary treatment to screen out the waste and next to stabilization ponds, then was passed on for use in the gardens inside the factory.

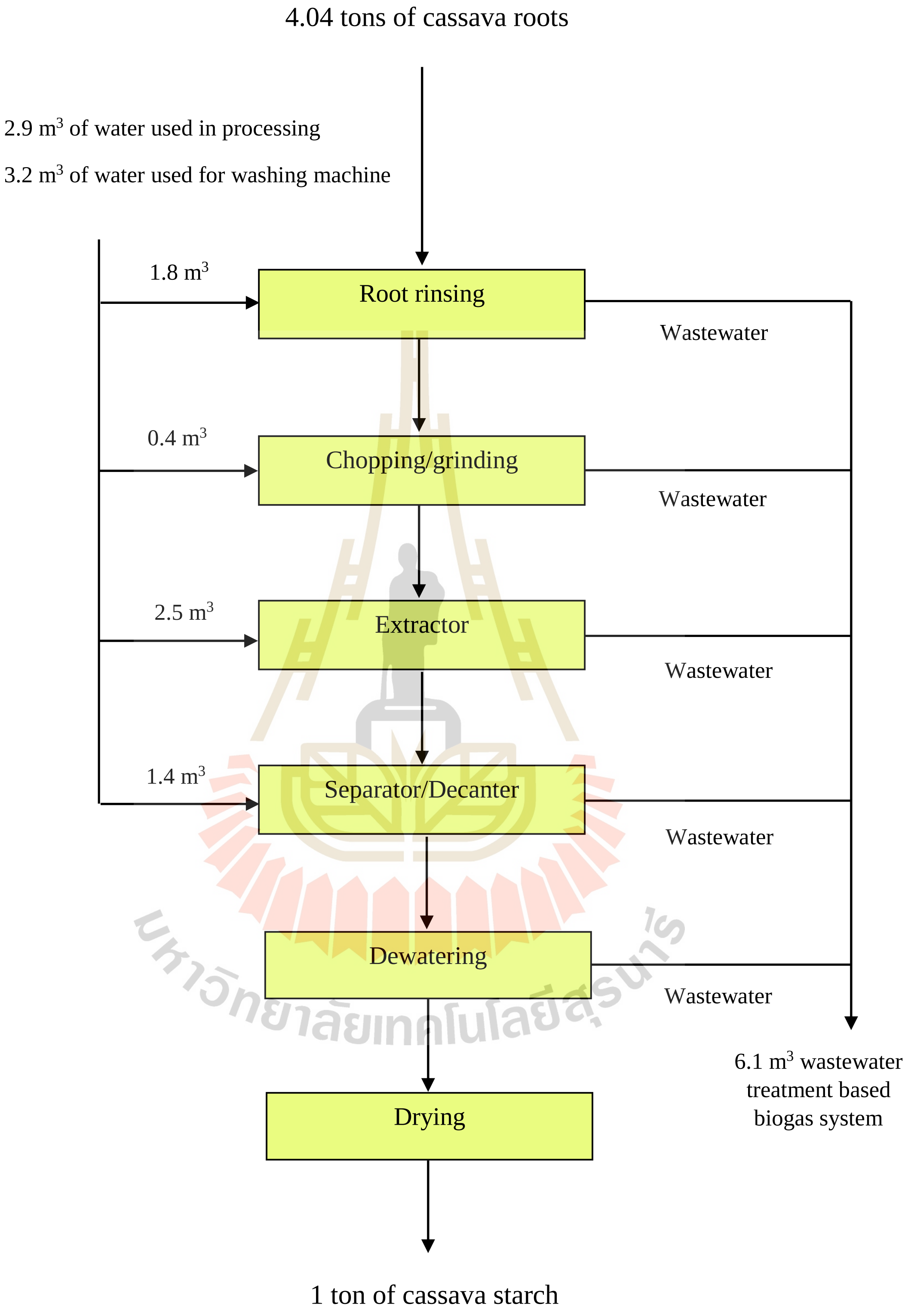


Figure 4.10 Process steps and water mass flow balance for the 2nd cassava starch factory.

Water consumption per one ton of cassava starch for the 2nd factory required 6.1 m^3, which was separated in each of the process steps equal to 1.8 m^3 for root rinsing, 0.4 m^3 for chopping/grinding, 2.5 m^3 for the extractor and 1.4 m^3 for the separator. Because water use in each of the process lines had been recycled within the water recycle plant the result was that the amount of water used was less than for the 1st factory. Water consumption was also used for both the processing and the washing machine. The amount of water used for processing was equal to 2.9 m^3, while the amount of water used for the washing machine was equal to 3.2 m^3. However, wastewater generation was drained directly into wastewater treatment based on a biogas system.

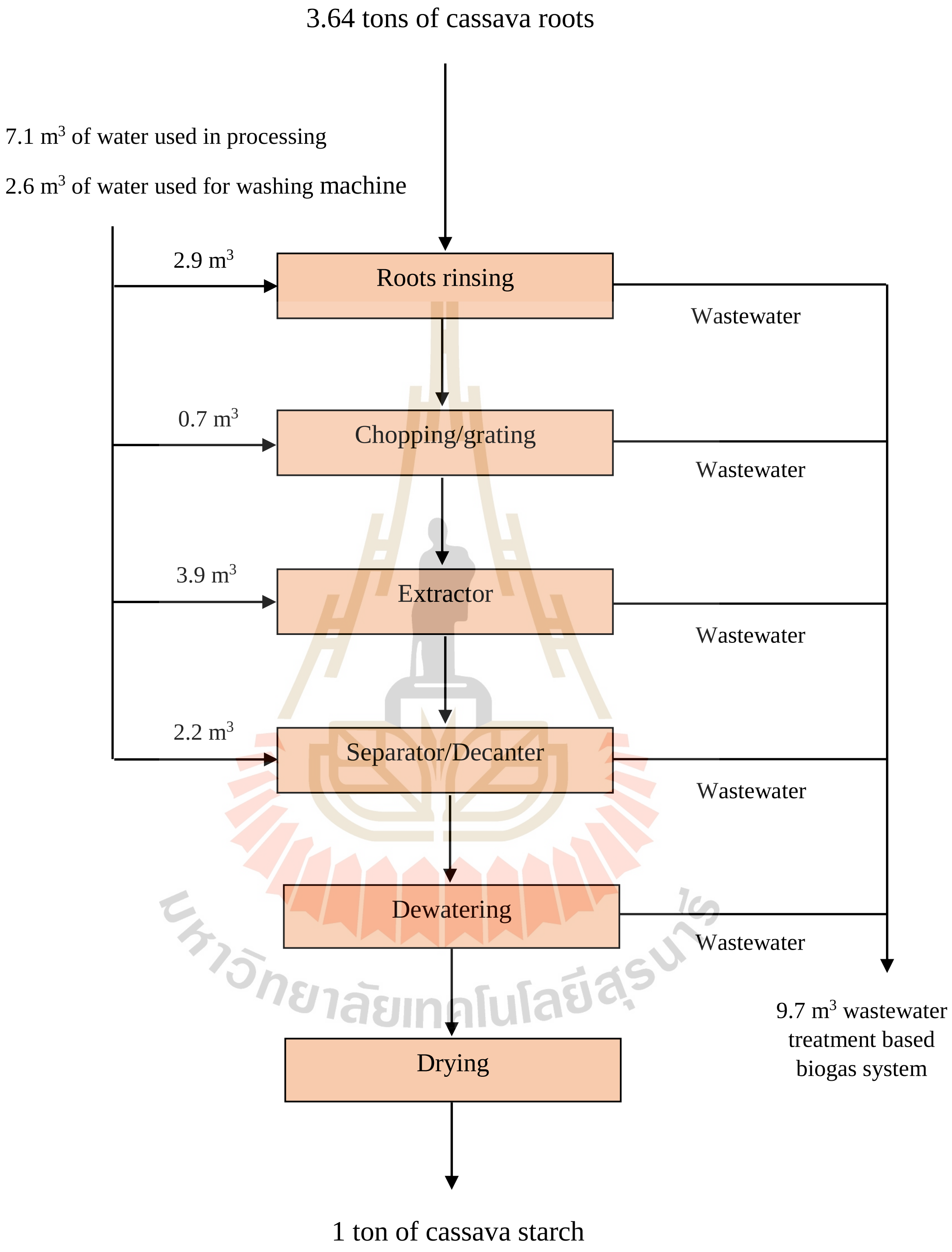


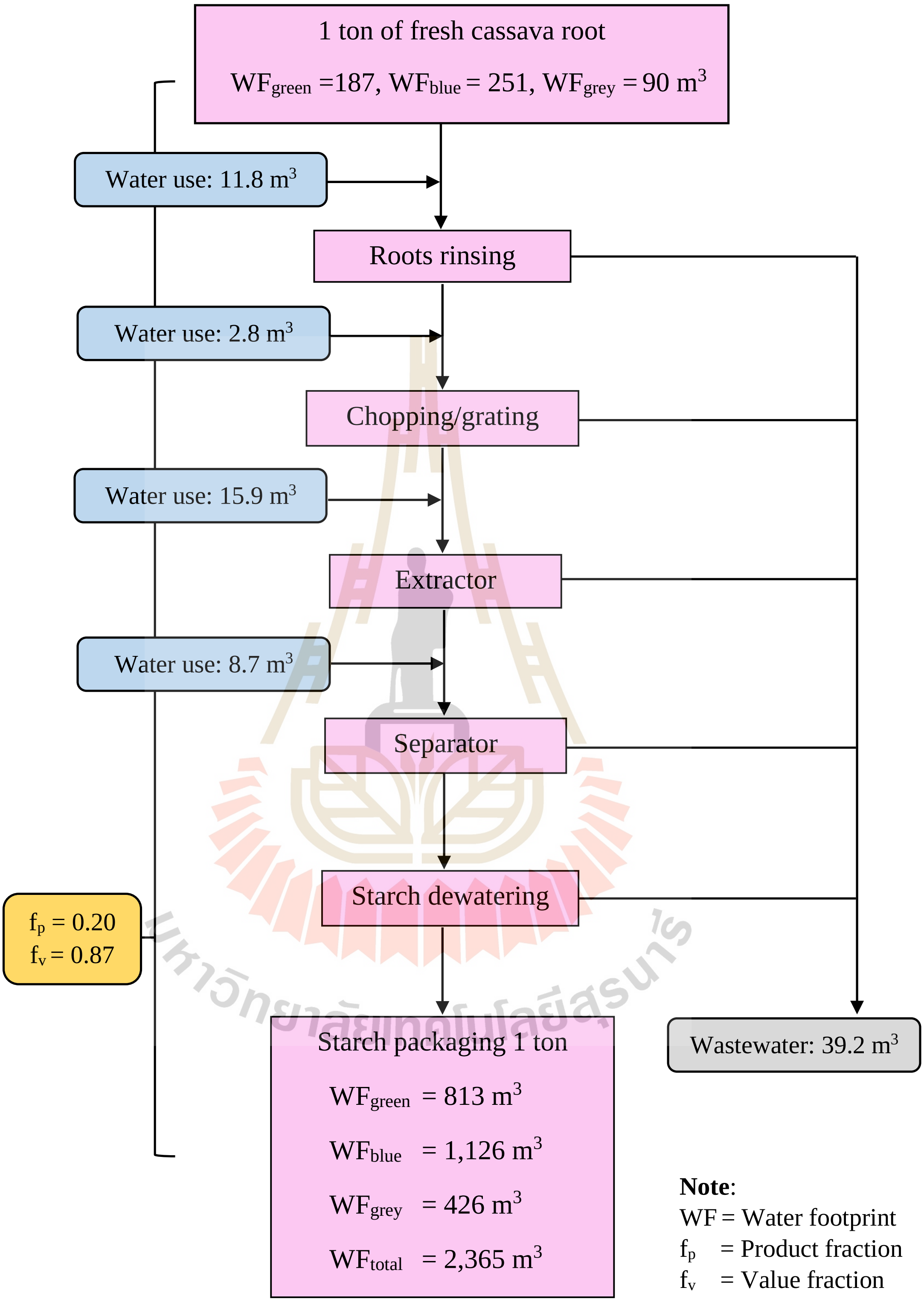
Figure 4.11 Process steps and water mass flow balance for the 3rd cassava starch factory.

Water consumption per one ton of cassava starch for the 3rd factory required 9.7 m^3 input in each of the process steps which was equal to 2.9 m^3 for root rinsing, 0.7 m^3 for chopping/grinding, 3.9 m^3 for the extractor and 2.2 m^3 for the separator. In this factory, the water consumption had been recycled within the water recycle plant that also was used for both the processing and washing machine with amounts of 7.1 m^3 and 2.6 m^3, respectively. The wastewater was drained directly into the wastewater treatment based on a biogas system.

4.2.2.2 Water footprint of product

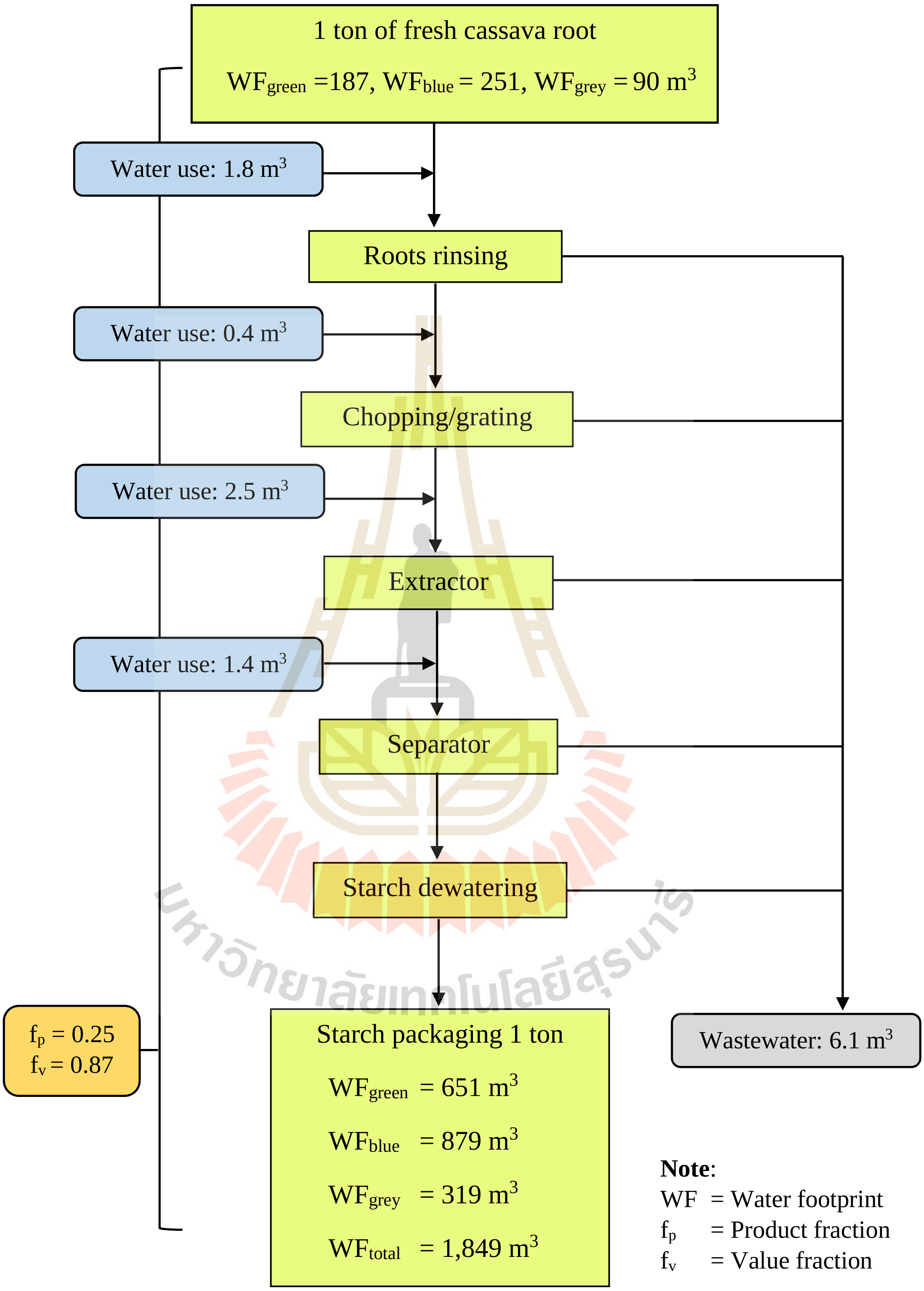
To estimate the WF of cassava starch starting with the amount of water used in cassava cultivation and transported into the cassava starch processing, a stepwise accumulative approach was used to calculate the amount of water during the processing. The WF of the product was generally expressed in terms of m^3/ton of cassava starch.

The average WF_{total} of cassava cultivation in Thailand was equal to 528 m^3/ton, including the green (187 m^3/ton), blue (251 m^3/ton) and grey (90 m^3/ton) WFs. Apart from this the water use in processing consumed from the surface water resource, the WF of the processing thus comprised both blue and grey components, but the green component in processing was equal to zero (there was no water use from the rainfall, green of $WF_{proc}[p] = 0$). Therefore, the water use in the crop cultivation and processing was applied to calculate the WF_{green}, WF_{blue} and WF_{grey} of cassava starch, followed by the equation (3.16). The product fraction was obtained from cassava starch processing in this study, whereas the value fraction was obtained from Khongsiri (2009). Figures 4.12, 4.13 and 4.14 present the WF of cassava starch from the different factories, which transformed fresh cassava roots into starch production.



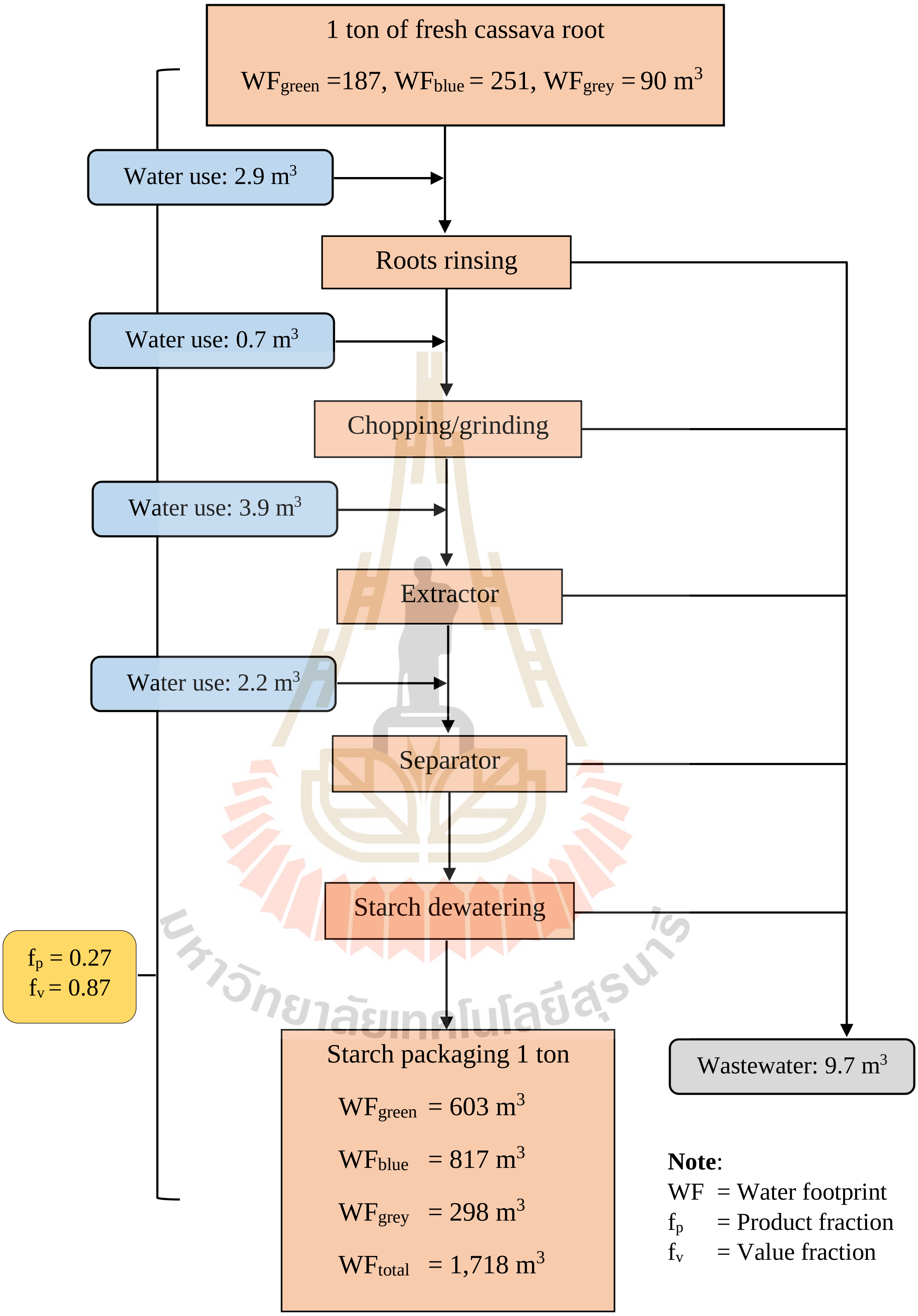
Note:
WF = Water footprint
f_p = Product fraction
f_v = Value fraction

Figure 4.12 Water footprint of cassava starch in the 1st factory.



Note:
WF = Water footprint
f_p = Product fraction
f_v = Value fraction

Figure 4.13 Water footprint of cassava starch in the 2nd factory.



Note:
WF = Water footprint
f_p = Product fraction
f_v = Value fraction

Figure 4.14 Water footprint of cassava starch in the 3rd factory.

The literature review of cassava starch processing obtained from previous Thai studies, the amount of water consumption from the LCI data was used to estimate the average WF of cassava starch of Thailand. The data is as follows:

1) Cassava starch processing studied by Khongsiri (2009)

Khongsiri (2009) used LCA methodology guidelines to create the LCI analysis through the cultivation, harvesting, transportation and processing in order to assess the environmental impacts of cassava starch. The data for inputs and outputs were collected from four cassava starch factories based on production from 2004 to 2006. This LCI data focused only on the amount of water use and wastewater generated in the processing that was used to apply the WF cassava starch calculation. The results revealed that the volume of water use on average of the four cassava starch factories based on one ton of starch required approximately 12.44 m^3, while water pollution in the form of wastewater loading was around 13.66 m^3, with BOD and COD loading of 127.570 and 256.131 kg, respectively.

2) Cassava starch processing studied by Chavalparit and Ongwandee (2009)

Eight cassava starch factories were selected covering all sizes of the categories, and classified according to the investment costs into three groups: large, medium and small factories, for the implementation of cleaner production to improve the environmental performance of cassava starch processing plants in Thailand. A detailed analysis was conducted using the existing data on the production process. The measurements of the production efficiency were conducted for 24 hours, and water consumption was recorded from plant water meters. The volume of water use per one ton of cassava starch required for manufacturing was approximately 18 m^3, and the water required for cassava root washing and fiber separation was made up of 70% of the total water use, while the wastewater generated about 19 m^3 with BOD loading of 135 kg.

3) Cassava starch processing as studied by Jakrawatana *et al.* (2016)

Jakrawatana *et al.* (2016) applied Material Flow Cost Accounting (MFCA) to identify the costs of materials and energy loss for technology improvement in starch and ethanol productivity. They collected the data from existing inputs and outputs from interviewing the plant managers and engineers of six cassava starch factories covering all the regions of Thailand. Moreover, the related data of cassava starch plants of Thailand which was collected during the literature review was used to proceed with the average LCI analysis. The results of this study showed that productivity from the different plants was similar, except for the energy use that was of medium uncertainty in the range of ±30%, while water use had a high uncertainty range at ±50%, because only some of the plants had a modified water cycle process in their systems. The results show that the average volume of water used was approximately 18 m^3 and the wastewater was generated at 21 m^3.

4) Cassava starch processing studied by Usubharatana and Phungrassami (2015)

The study of the carbon footprint of cassava starch production in Northeastern Thailand used the LCA methodology guidelines. A cradle to gate life cycle assessment was used to collect the data for inputs and outputs starting from cassava cultivation, harvesting till starch processing. In this study only the cassava starch processing part was used to calculate the WF. Water consumption per one ton of cassava starch from the three factories: FA, FB and FC required 14.75, 16.86 and 22.96 m^3, respectively. The average of the three plants was equal to 18.19 m^3. This research did not report on the output products such as wastewater generation, and it was assumed that the wastewater was equal to the amount of water use for processing in order to estimate the WF_{grey}.

According to all literature reviews of LCI data of cassava starch processing which are based on one ton of starch, the data concerning water use and wastewater in each of their processes were applied to calculate the WF_{green}, WF_{blue} and WF_{grey} of cassava starch by using a similar method to the equation (3.16). Therefore, the average WF of cassava starch in Thailand was pooled from previous Thai studies and from the results of this study as shown in Table 4.20.

Table 4.20 Average water footprint of cassava starch in Thailand.

Authors	Number of case factories	WF of cassava starch production (m^3/ton of starch)			
		Green	Blue	grey	Total
In this study	3	689	941	348	1,978
Khongsiri (2009)	4	775	1,051	385	2,211
Chavalparit and Ongwandee (2009)	8	678	926	343	1,947
Jakrawatana *et al.* (2015)	6	678	926	345	1,949
Usubharatana and Phungrassami (2015)	3	603	825	306	1,734
Average		**684**	**933**	**345**	**1,962**

The results from Table 4.20 show the average total WF per one ton of cassava starch in this study and based on the literature reviews of previous Thai studies present a range of 2,211-1,734 m^3/ton, related with the largest and lowest from

Khongsiri, Usabharatana and Phungrassami, respectively. However, the average total WF of cassava starch of Thailand was estimated at 1,962 m^3/ton, and classified into green, blue and grey components that were 684, 933 and 345 m^3/ton, respectively. The blue component is still significant with water resource policy management more than the green and the grey components, because it has a higher economic value for limited surface water resources. Thes average WF of cassava starch of Thailand will be used to calculate the virtual water flow (VWF) of product trade in the third part of this study.

4.2.3 Water footprint of refined sugar

4.2.3.1 Processing and inventory data analysis

The amount of water consumption from a refined sugar factory that is located in Nakhon Ratchasima province was selected to estimate the water mass flow balance per one ton of refined sugar, and it was applied to calculate the WF of refined sugar. The water use in this study has been reused and recycled by the waste from the output process lines which were divided into various input process steps. Measuring the water use that applied from surface water was recorded by a water meter, whereas the amount of the wastewater was measured by investigators.

The water mass flow balance of refined sugar processing based on one ton of product as shown in Figure 4.15 gives the amount of water use and waste by process steps that were reused and recycled throughout the refined sugar processing.

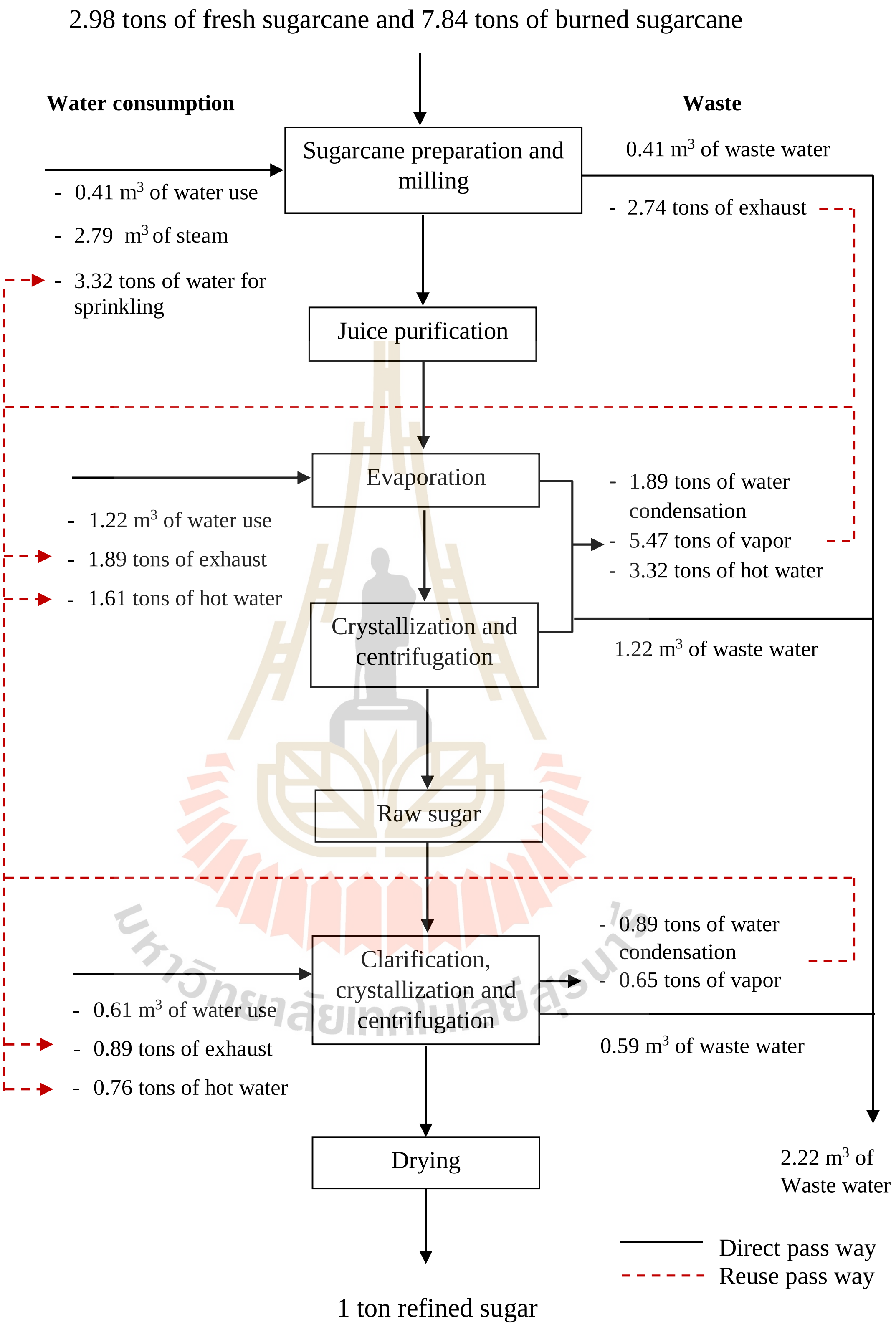
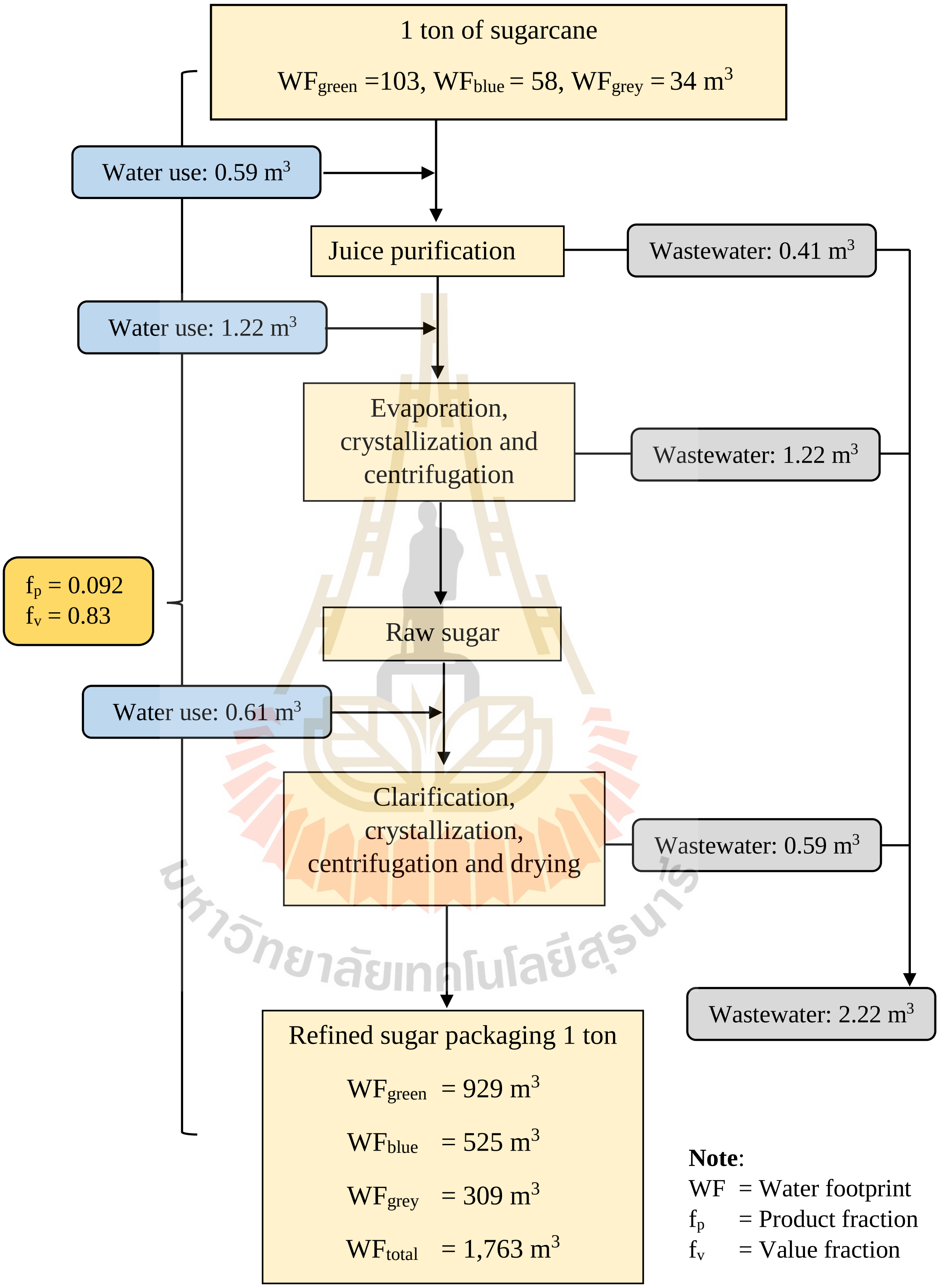


Figure 4.15 Process steps and water mass flow balance of refined sugar processing.

The total water use taken to produce one ton of refined sugar production was approximately 2.24 m^3. Steam was used in juice extraction processing, which revealed that about 2.79 tons was produced by 0.18 m^3 of fresh water. Thus, the net water use for processing required 2.42 m^3, most of which was saturated for juice extraction that was made up of 53.2%, followed by raw sugar (31.2%) and refined sugar (15.6%). Waste outputs from hot water, water condensation and vapor were recycled and returned into the input product, while water pollution such as wastewater was generated at about 2.22 m^3.

4.2.3.2 Water footprint of product

To estimate the WF_{green}, WF_{blue} and WF_{grey} of refined sugar a similar calculation was used as for cassava starch. As the result of WF of sugarcane cultivation revealed 195 m^3/ton including the green (103 m^3/ton), blue (58 m^3/ton) and grey (34 m^3/ton) components that were applied to calculate the WF of the prodcut. In this study water consumption in processing could be applied from surface water that was treated in a water supply plant, while the wastewater generated through the production process was drained into wastewater treatment based on a biogas system. Therefore, water use which contributed to refined sugar processing consisted of the blue and grey components (there was no green component because there was no water use from the rainfall, as green $WF_{proc}[p] = 0$). On the other hand, the product fraction was obtained from this study, whereas the value fraction was obtained from Scholten (2009). Figure 4.16 presents the assessment of WF of refined sugar that transforms fresh and burned sugarcane into refined sugar processing.



Note:
WF = Water footprint
f_p = Product fraction
f_v = Value fraction

Figure 4.16 Water footprint of refined sugar.

The amount of water use from LCI data for refined sugar processing in previous Thai studies referred to in literature review was used to estimate the average WF of refined sugar in Thailand. The data is as follows;

1) Refined sugar processing studied by Witayapairot (2010)

This research study was conducted to develop the LCI analysis, which consists of resource and energy use and pollutant releases, and to evaluate the environmental impact associated with one ton of sugarcane. The LCI analysis followed the LCA methodology guidelines. The scope of this research started with planting, maintaining, cultivating, transporting and milling (cradle to gate), whereas only the refined sugar processing part was used to calculate the WF of the product. This processing required important sources: sugarcane, water, energy and the chemicals associated with an environmental impact assessment. In order to assess the WF of the product, water consumed was equal to 1.45 m^3. In addition, this research study did not reveal data about wastewater generation, as it was assumed that the amount of wastewater was equal to the amount of water used for processing.

2) Refined sugar processing as illustrated by the Department of Industrial works, Thailand (2013)

The purpose of this research was to develop an inventory database in order to apply it to the environmental impact assessment. The Sima Pro 7.3.3 software work was used in this research for assessing the carbon footprint of refined sugar following the LCA methodology guidelines that are generally accepted. The data for the inputs and outputs from the factories were collected from November to October, in follow year, starting with transporting and then milling (gate to gate). Water consumption, energy used, steam processing, pollution and wastewater generation were recorded within practical limitations. The inputs and outputs data sources were obtained from the inventory data collection sheets from many factories and monitoring reports on the environment and pollution by investigators. The results showed that the total water consumption required for one ton of refined sugar production throughout processing was at 5.86 m^3, whereas the amount of wastewater was 4.53 m^3.

According to the two literature reviews of refined sugar processing, the amount of water use and wastewater generation were used to calculate the WF as in the following equation (3.16). Therefore, the average WF of refined sugar in Thailand pooled from previous studies and from the results of this study is shown in Table 4.21.

Table 4.21 Average water footprint of refined sugar production in Thailand.

Authors	Product fraction	WF of refined sugar (m^3/ton)			
		Green	Blue	Grey	Total
In this study	0.092	929	525	309	1,763
Witayapairot (2010)	0.032	2,672	1,506	883	5,061
DIW, Thailand (2013)	0.018	4,749	2,682	1,573	9,004
Average of Thailand	**-**	**2,783**	**1,571**	**922**	**5,276**

The results show that the total WF of refined sugar production in Thailand has a wide range (between 1,763-9,004 m^3/ton), because the production process is similar among the factories, but they may use different techniques and machines for each production stage. Moreover, it depends on the percent of refined sugar purification needs which affect on the differences in the amount of water consumption. However, the average total WF of refined sugar production in Thailand was 5,276 m^3/ton, classified into the green, blue and grey components which were 2,783, 1,571 and 922 m^3/ton, respectively.

With regard to the studies of the WF of products produced from different crops in Thailand, they were diverse and different in each region depending on their respective geographical and climatic conditions (Gheewala *et al.*, 2014). Not many previous studies in Thailand have used the WF concept to estimate the water use in crop cultivation linked with their products, as shown in Table 4.22.

A comparison of the data from Table 4.22, which consists of the production of rice flour, raw sugar and palm oil, found that the amount of water used to produce palm oil was the highest (5,083 $m^{3/}$ton) followed by rice flour (2,737 m^3/ton) and raw sugar (1,745 $m^{3/}$ton), respectively. The raw sugar production results showed that the WF varied according to the different types of raw sugar which might also depend on the purification needs of raw sugar production. For rubber production, the rubber was processed into two types as ribbed smoked sheets (RSS) and ribbed smoked sheet bales (RSSB) that showed the total WF was around 549 and 592 m^3/ton, respectively. For other products, Mekonnen and Hoekstra (2011) revealed that the global average WF of cassava starch was equal to 2,254 m^3/ton, while raw sugar and refined sugar made from cane was equal to 1,666 and 1,782 m^3/ton, respectively.

Table 4.22 Water footprint of products obtained from important crops.

Authors	Product	Study area	Water footprint (m^3/ton)			
			Green	Blue	Grey	Total
In Thailand						
Wangmuang and Sachakamol (2011)	Rice flour in production process	Northeastern	-	-	-	4.5
		Eastern	-	-	-	1.5
Wangmuang (2012)	Rice flour product	Average in whole country	-	-	-	2,737
Ngamsomrit (2013)	Raw sugar-J-Spec	Northern	379	218	66	663
	Raw sugar-Hi-Pol	Northern	218	123	38	379

Table 4.22 (Continued).

Authors	Product	Study area	Water footprint (m^3/ton)			
			Green	Blue	Grey	Total
	Raw sugar-W3	Northern	20	18	4	42
	Raw sugar	Northern	995	576	174	1,745
Suttayakul *et al.* (2016)	Palm oil product	Average on Southern and Eastern	3,507	813	763	5,083
Musikavong and Gheewala (2016)	Ribbed smoked sheet	9 provinces in Southern	-	-	-	549
	Ribbed smoked sheet bales	2 provinces in Southern	-	-	-	592
Other						
Mekonnen and Hoekstra (2011)	Cassava starch	Global on average	2,200	1	53	2,254
	Raw sugar, cane	Global on average	1,107	455	104	1,666
	Refined sugar, cane	Global on average	1,184	487	111	1,782

4.2.4 Comparison of the water footprint for cassava starch and refined sugar

The WF of cassava starch and refined sugar in Thailand was classified into green, blue and grey components. Based on the average WF of product per one ton, cassava starch required about 1,962 m^3 which comprised green (684 m^3), blue (933 m^3) and grey (345 m^3), and refined sugar required about 5,276 m^3 which comprised green (2,783 m^3), blue (1,571 m^3) and grey (922 m^3).

Table 4.23 Water footprint of cassava starch and refined sugar.

Products	Water footprint (m^3/ton)			
	Green	Blue	Grey	Total
Cassava starch	684	933	345	1,962
Refined sugar	2,783	1,571	922	5,276

The impact of water consumption for cassava starch and refined sugar in Thailand is mainly on blue water resources, which the freshwater evaporates or assimilates the pollution during the production process. Blue water has an impact on the economic cost because blue water (surface or groundwater) has a relatively high economic cost since it has to be pumped and transported through pipes or irrigation equipment before being applied to the crops, whereas green water (rainfall) is distributed directly for crop cultivation. Although rainwater will often have no alternative use, the economic value of rainwater should be included in the price of the product (Chapagain and Hoekstra, 2007) in the same way as for the blue and grey. For instance, the price of one ton of cassava starch is equal to 11,000 baht (Thai Tapioca Starch Association, 2017), the total water used to produce its product requires 1,962 m^3 which means that the price of 1 m^3 of water use is embedded in the price of the product which is equal to 5.6 baht. In the case of refined sugar, the price of one ton of refined sugar is equal to 23,500 baht (Office of the Cane and Sugar Board, 2017), which requires 5,276 m^3 of the total water use that implies the price of 1 m^3 of water that is embedded in the price product which is equal to 4.5 baht. The water consumption required to produce the different productions as cassava starch and refined sugar of Thailand can conclude that the total amount of water needed for cassava starch is less than for refined sugar as it is less than twice. In addition, the total water needed to produce cassava starch has a greater economic value more than refined sugar.

4.3 Virtual water flow of trade cassava starch and refined sugar

4.3.1 Cassava starch

4.3.1.1 Export and import market of cassava starch

According to Poramacom *et al*. (2013) in chapter II, who reported that cassava roots produced 55% of cassava starch (40% pellets and 5% ethanol remaining) that was divided into domestic consumption of 19% and worldwide export of 36%. Cassava starch export smostly contributed to the developed and developing countries, especially in Asia. The top twenty major markets of cassava starch exported from Thailand, during 2008-2013, as reported by OAE (2014) are shown in Table 4.24. The data revealed the top five largest importer countries accounted together for 80% in China (31%), Indonesia (18%), Taiwan (14%), Malaysia (10%) and Japan (7%), respectively. These amounts of exported cassava starch for Asia were over 85%, USA 2.3%, Europe and Netherlands and Russia together were 0.9%. Moreover, Australia and New Zealand together imported 1.2%, whereas South Africa imported 1%.

Table 4.24 Cassava starch exported from Thailand by importer country (OAE, 2014).

Countries	Thailand cassava starch export (ton/year)						
	2008	2009	2010	2011	2012	2013	Average
China	236,900	500,943	546,827	502,255	565,550	1,185,278	589,625
Indonesia	157,472	241,668	274,385	462,327	663,247	236,607	339,284
Taiwan	229,264	313,365	248,654	266,737	253,090	285,535	266,108
Malaysia	131,396	188,351	186,697	210,862	259,847	191,313	194,744
Japan	156,018	123,214	101,461	124,136	140,624	127,268	128,787
Philippines	33,347	70,027	59,140	50,440	57,126	56,223	54,384
Singapore	46,815	50,644	38,469	45,048	48,670	61,362	48,501
USA	27,866	31,715	45,931	35,875	59,332	60,337	43,509
Bangladesh	31,213	37,275	35,750	26,138	20,227	31,048	30,275
South Korea	26,315	36,893	10,504	23,450	42,818	31,843	28,637
Hong Kong	29,763	31,409	27,456	17,270	19,031	21,335	24,377
Australia	15,491	25,565	11,471	11,580	15,355	19,800	16,544
South Africa	23,172	13,607	17,211	15,476	15,006	12,558	16,171
Saudi Arabia	18,399	17,588	9,979	11,155	5,311	12,646	12,513

Table 4.24 (Contined).

Countries	Thailand cassava starch export (ton/year)						
	2008	2009	2010	2011	2012	2013	Average
Netherlands	8,021	6,671	21,287	12,308	10,158	11,373	11,636
India	922	16,635	20,028	557	203	6,098	7,407
New Zealand	8,750	7,621	5,292	4,899	6,716	5,026	6,384
Russia	13,180	7,881	3,305	6,750	1,198	3,128	5,907
Vietnam	511	1,197	23,907	502	123	8,376	5,769
UAE	5,176	10,796	6,220	5,691	1,074	1,716	5,112
Others	72,176	65,036	46,832	57,890	50,867	76,744	61,591

Thailand sometimes requires that carbohydrate like flour will be modified in the industrial sector, so Thailand needs to import a few of these products from other countries. During the period 2008-2013 it was reported by the OAE (2014) that the most important sources were from South East Asia (Table 4.25): Lao PDR and Thailand together were 41.7% of the total amount imported. Other sources were Vietnam (14.5%), Myanmar (12.0%) and Cambodia (11.7%), respectively. The gross national import of cassava starch to Thailand is shown in Table 4.25.

Table 4.25 Cassava starch imported to Thailand by exporter country (OAE, 2014).

Countries	Thailand cassava starch import (ton/year)						
	2008	2009	2010	2011	2012	2013	Average
Lao, PDR	-	-	-	123	1,735	136	332
Thailand	53	94	439	221	201	494	250
Vietnam	-	-	190	-	390	632	202
Myanmar	-	-	-	-	1,003	-	167
Cambodia	-	-	128	-	851	-	163
Indonesia	-	-	-	121	279	523	154
South Korea	-	130	170	-	-	-	60
China	-	-	33	108	3	-	29
USA	7	3	10	25	21	98	27
Japan	1	4	23	10	2	6	8
Others	1	2	7	1	3	6	4

4.3.1.2 The net virtual water flow of trade cassava starch

The VWF of trade cassava starch export or import was calculated by multiplying the volumes of cassava starch exports or imports (in tons/year) and the average WF of cassava starch (in m^3/ton). The difference between VWF of export and import was the net VWF of their trade, which is an indicator for the total amount of water needed to produce cassava starch that exported or imported of a nation. The quantity of cassava starch imports was very low compared to the exports. Thus, the net VWF of trade cassava starch in Thailand is associated with their export quantity.

Table 4.26 The net virtual water flow of cassava starch export in Thailand.

Countries	Net virtual water flow of export (Mm^3/year)			
	Green	Blue	Grey	Total
China	403.28	548.32	199.28	1,150.89
Indonesia	231.97	315.39	114.62	661.98
Taiwan	182.02	247.48	89.94	519.44
Malaysia	133.21	181.11	65.82	380.14
Japan	88.08	119.76	43.53	251.38
Philippines	37.20	50.74	18.87	106.81
Singapore	33.18	45.25	16.83	95.26
USA	29.74	40.57	15.09	85.40
Bangladesh	20.71	28.25	10.51	59.46
South Korea	19.55	26.66	9.92	56.13
Hong Kong	16.67	22.74	8.46	47.88
Australia	11.32	15.44	5.74	32.49
South Africa	11.06	15.09	5.61	31.76
Saudi Arabia	8.56	11.67	4.34	24.58
Netherlands	7.96	10.86	4.04	22.85
India	5.07	6.91	2.57	14.55
New Zealand	4.37	5.96	2.22	12.54
Russia	4.04	5.51	2.05	11.60
Vietnam	3.81	5.19	1.93	10.93
UAE	3.50	4.77	1.77	10.04
Lao, PDR*	0.23	0.31	0.11	0.65
Thailand*	0.17	0.23	0.08	0.48
Myanmar*	0.11	0.16	0.06	0.33
Cambodia*	0.11	0.15	0.06	0.32
Others	39.73	54.19	20.16	120.96
Total	**1294.38**	**1761.03**	**643.00**	**3,698.40**

Remark: * was the net VWF of import.

The net VWF_{total} of cassava starch exports from Thailand in the period of 2008-2013, which was estimated at 3.70 Gm^3/year, consists of green (1.30 Gm^3/year), blue (1.76 Gm^3/year) and grey (0.64 Gm^3/year), respectively. China was the largest importer that accounted for 1,150.89 Mm^3/year. Other importer countries in decreasing order were Indonesia (661.98 Mm^3/year), Taiwan (519.44 Mm^3/year), Malaysia (380.14 Mm^3/year) and Japan (251.38 Mm^3/year). Some of the amount of VWF was released to USA (85.40 Mm^3/year), Netherlands in Europe (22.85 Mm^3/year) and Russia (11.60 Mm^3/year), while some was released to Australia (32.49 Mm^3/year) and New Zealand (12.54 Mm^3/year), and another amount was released to South Africa (31.76 Mm^3/year). On the other hand, the net VWF of cassava starch imports to Thailand, showed that Lao PDR was the largest source into Thailand that contributed 0.65 Mm^3/year, followed by Thailand (0.48 Mm^3/year) and Myanmar (0.33 Mm^3/year).

This information shows that Thailand exported cassava starch around the world, especially within Asia. Although, the original source of cassava crop is mostly produced in Central and South East Asia, many countries do not produce enough and consume what they produce themselves.

The global cassava starch exports reported by FAO (2012) revealed an amount of about 2 billion ton/year and 90% being contributed worldwide from Thailand. With regard to the net VWF of cassava starch exports from Thailand that shows how much water is used (especially surface water resource) to produce cassava starch production for exports, the water use for agricultural practices throughout production process from cassava roots to cassava starch production required amounts of freshwater flowing out of Thailand to other countries. In this research, it is reported that cassava starch production could use 1,962 $m^{3/}$ton of water on average, or about

3.70 Gm^3/year that contributed to supporting cassava starch consumption in other countries. Most countries that imported cassava starch relied on imports from Thailand, even if these countries were facing water scarcity, the commodity was imported to save water resource consumption in them.

4.3.2 Refined sugar

4.3.2.1 Export and import market of refined sugar

The opportunities of supplying sugar to the growing markets in Asia have encouraged Thailand to expand its sugar production. Thailand has become one of the world's leading sugar exporters under the Thai government policy of maintaining a high productivity and increasing exporst (FAO, 1997). The top twenty major markets for Thailand's refined sugar export in the period of 2008-2013, recorded by OAE (2014) (Table 4.27) revealed that about 46% of all refined sugar was exported to South East Asia, and over 90% to Asia. Cambodia was the largest importer, followed by Indonesia, Iraq, Vietnam and India, respectively.

Table 4.27 Refined sugar exported from Thailand by importer country (OAE, 2014).

Countries	Thailand refined sugar export (ton/year)						
	2008	2009	2010	2011	2012	2013	Average
Cambodia	314,031	434,754	380,786	400,470	550,461	624,574	450,846
Indonesia	467,484	123,456	496,147	89,084	125,117	67,148	228,073
Iraq	250,060	182,825	57,792	331,406	350,106	150,201	220,398
Vietnam	47,575	97,376	169,392	235,100	228,581	139,109	152,856
India	-	340,654	316,084	6,650	6,989	6,987	135,473
Philippines	97,889	89,367	282,722	156,984	78,528	69,989	129,246
Singapore	92,513	110,048	100,109	166,917	127,703	107,399	117,448
Taiwan	160,492	125,044	27,080	81,240	92,134	110,210	99,367
China	80,573	68,899	17,832	72,746	138,533	213,776	98,726
Sudan	-	65,900	112,222	65,465	5,592	214,875	92,811
Tunisia	-	-	-	64,325	-	-	64,325
Malaysia	33,018	24,545	36,754	33,359	99,314	152,750	63,290
Sri Lanka	24,942	120,834	59,975	38,563	49,925	49,800	57,340
Pakistan	17,900	139,265	157,855	2,525	1,025	178	53,125

Table 4.27 (Continued).

Countries	Thailand refined sugar export (ton/year)						
	2008	2009	2010	2011	2012	2013	Average
Lao PDR	10.5	45,789	27,577	46,812	80,576	29,760	46,506
UAE	50,694	97,695	19,736	43,118	12,504	24,798	41,424
Djibouti	-	2,981	-	-	-	78,650	40,815
Myanmar	4,278	5,492	12,057	30,529	46,013	113,845	35,369
Ghana	138	1,630	-	26,500	117,375	825	29,294
Jordan	1,150	16,050	-	11,294	46,723	61,850	27,413
Others	342,752	611,853	151,576	495,258	441,837	648,604	448,647

The refined sugar imported to Thailand for domestic consumption depends on the demand and supply of refined sugar in the world market. The average amount of refined sugar imported to Thailand recorded by OAE (2014) revealed UAE, UK and Myanmar were the biggest exporter countries, which were over 90% of the total imports. However, the quantities of refined sugar imported were very low compared with exports. The gross national import of Thai refined sugar production is specified in Table 4.28.

Table 4.28 Refined sugar imported to Thailand by exporter country (OAE, 2014).

Countries	Thailand refined sugar imported (ton/year)						
	2008	2009	2010	2011	2012	2013	Average
UAE	2	2	3,720	9,783	-	2	2,251
UK	-	-	7,200	2,800	16	-	1,669
Myanmar	2,371	-	-	-	-	-	395
Indonesia	180	456	281	116	198	-	205
Thailand	144	22	20	-	74	211	79
USA	-	-	41	38	55	60	32
Philippines	-	-	12	165	-	-	29
Belgium	25	13	70	33	7	17	27
Singapore	32	20	-	17	-	-	11
Japan	-	4	2	-	20	2	5
Others	8	9	62	23	24	12	23

4.3.2.2 The net virtual water flow of trade refined sugar

The net VWF_{total} of refined sugar was calculated by the same method as for cassava starch following the equation (3.19). The quantity of refined sugar imports was very low when compared to their exports. Thus, the net VWF of trade refined sugar of Thailand is dependent on the export quantity. The results are illustrated in Table 4.29.

Table 4.29 The net virtual water flow of refined sugar export in Thailand.

Countries	Virtual water flow of export (Mm^3/year)			
	Green	Blue	Grey	Total
Cambodia	1,254.70	708.28	415.68	2,378.66
Indonesia	634.16	357.98	210.09	1,202.23
Iraq	613.37	346.25	203.21	1,162.82
Vietnam	425.40	240.14	140.93	806.47
India	377.02	212.83	124.91	714.75
Philippines	359.61	203.00	119.14	681.75
Singapore	326.83	184.49	108.28	619.60
Taiwan	276.54	156.11	91.62	524.26
China	274.76	155.10	91.03	520.88
Sudan	258.29	145.81	85.57	489.67
Tunisia	179.02	101.05	59.31	339.38
Malaysia	176.14	99.43	58.35	333.92
Sri Lanka	170.41	93.29	54.42	318.12
Pakistan	147.85	83.46	48.98	280.29
Lao PDR	129.43	73.06	42.88	245.36
UAE	115.28	65.08	38.19	218.55
Djibouti	113.59	64.12	37.63	215.34
Myanmar	97.33	54.94	32.25	184.52
Ghana	81.52	46.02	27.01	154.55
Jordan	76.29	43.07	25.28	144.63
UK*	4.65	2.62	1.54	8.81
Thailand*	0.22	0.12	0.07	0.41
USA*	0.09	0.05	0.03	0.17
Belgium*	0.08	0.04	0.03	0.14
Japan*	0.01	0.01	0.00	0.02
Others	1,248.52	704.79	413.63	2,366.94
Total	**7,324.74**	**4,131.90**	**2,424.62**	**13,881.26**

Remark: * was the net VWF of import.

The net VWF_{total} of trade refined sugar export of Thailand pooled for the year 2008-2013, was estimated at around 13.88 Gm^3/year, which was composed of 7.32, 4.13 and 2.42 Gm^3/year of green, blue and grey components, respectively. The top five largest countries with VWF of exports were Cambodia (2.38 Gm^3/year), Indonesia (1.20 Gm^3/year), Iraq (1.16 Gm^3/year), Vietnam (0.81 Gm^3/year) and India (0.71 Gm^3/year). This information shows that the importer countries from Asia, especially South East Asia generally consumed the VWF of exports from Thailand. Because many countries in Asia consume large amounts of refined sugar derived from sugarcane, they do not produce enough sugar for themselves, while the developed countries such as Europe or America are also sugar producers and sometimes importers of raw sugar from various exporter countries, in order to produce refined sugar that depends on the world's demand and supply of sugar or their quota.

The information about VWF of exports and imports of commodities trade are attended to account for the water resources related to its trade. If the exporter country is definitely too large an exporter of commodities, that will be have a negative impact on their environment, especially its water resources. An understanding of water impacts is one criterion when making decisions, and it is a crucial element in determining how we can adapt to the challenges facing our growing population demand on limited water resources (Chapagain and Orr, 2009).

The overall results estimated under the irrigation schedule-option of WF and VWF of trade cassava starch and refined sugar in Thailand is shown in Table 4.30.

Table 4.30 The overall results of water footprint and virtual water flow of trade cassava starch and refined sugar in Thailand during 2008-2013.

Products	Green	Blue	Grey	Total
Cassava starch				
- Crop water use (m^3/ha)	3,863	5188	-	9,051
- Water footprint of crop cultivation (m^3/ton)	187	251	90	528
- Water footprint of product (m^3/ton)	684	933	345	1,962
- Virtual water flow of trade (Gm^3/year)	1.30	1.76	0.64	3.70
Refined sugar				
- Crop water use (m^3/ha)	7,547	4,219	-	11,766
- Water footprint of crop cultivation (m^3/ton)	103	58	34	195
- Water footprint of product (m^3/ton)	2,783	1,571	922	5,276
- Virtual water flow of trade (Gm^3/year)	7.32	4.13	2.42	13.88

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The WF is an important indicator of how much water is needed to produce a product or a service. It can provide us with a clear picture of how to project the amount of water use on a domestic or a national scale related to a product or a service consumed. This study comprises three parts, first, to estimate the WF of cassava and sugarcane cultivation in Thailand during the period of 2008-2013. Second, to calculate the WF of cassava starch and refined sugar production and, finally, to estimate the VWF trade of these products. The results of this study are as follows:

5.1.1 Water footprint and virtual water flow of trade cassava starch

In the first part, to estimate WF of cassava cultivation, including the calculation of the CWU_{eva} and WF_{eva} of cassava cultivation using the CROPWAT 8.0 program, the results show the ET estimated under the CWR-option (option 1) was slightly higher than under the irrigation schedule-option (option 2), because the crops were grown under non-standard conditions, and soil conditions and soil water stress affected the crop transpiration that made the ET_a low in option 2. Moreover, in each province, both options found that the amount of green and blue components was quite different, since it depends on the climate and soil conditions under which crops are grown. The average CWU_{eva} and WF_{eva} was found to be the largest in the Northeastern region, followed by the Central Plain and Northern regions, respectively. An analysis of the components of the WF revealed that the blue component was greater than the green and grey. The average CWU_{eva} estimated under the CWR-option found that in the whole country it was about 9,074 m^3/ha, consisting of CWU_{green} (4,012 m^3/ha) and CWU_{blue} (5,062 m^3/ha), while the WF_{eva} for the whole country was estimated at 439 and m^3/ton, comprising WF_{green} (194 m^3/ton) and WF_{blue} (245 m^3/ton). On the other hand, the estimate of the average CWU_{eva} under the irrigation schedule-option for the whole country was 9,051 m^3/ha, consisting of CWU_{green} (3,863 m^3/ha) and CWU_{blue} (5,188 m^3/ha), whereas the average WF_{eva} for the whole country was estimated at about 438 m^3/ton, comprised of WF_{green} (187 m^3/ton) and WF_{blue} (251 m^3/ton). The assessed value of WF_{grey} was found to be the highest in the Northeastern region, followed by the Northern region and the Central Plain, which was around 99, 86 and 79 m^3/ton, respectively, and the average value for the whole country was 90 m^3/ton. Therefore, the amount of water use for cassava cultivation estimated under the irrigation schedule-option, with the WF_{total} as the summation of green, blue and grey components, resulted in the average for the whole country of about 528 m^3/ton.

In the second part, the WF of cassava starch was calculated. With regard to production process, information was collected about the amount of water use from three factories in order to obtain the water mass flow balance based on one ton of starch that was applied to calculate the WF of product (the amount of water use from the crop cultivation transformed into cassava starch). Moreover, the water use in the cassava starch processing from LCI data (data from previous studies of Thailand referred to in the literature review) and the data of this study were used for weighting the average WF of cassava starch. The WF of cassava cultivation was obtained only under the irrigation schedule-option as the WF input to calculate the WF of cassava starch. The results show that the WF_{total} was 1,962 m^3/ton, consisting of green (684 m^3/ton), blue (933 m^3/ton) and grey (345 m^3/ton).

In the final part, the net VWF of trade cassava starch was determined. This is the difference between VWF of exports and import of products that are traded worldwide. The VWF was an indicator for the total amount of water needed to produce cassava starch within a country that flowed out to other countries. The results show the VWF of export was much larger than the VWF of imports. The net VWF_{total} of trade cassava starch exports from Thailand was estimated at 3.70 Gm^3/year, consisting of green (1.30 Gm^3/year), blue (1.76 Gm^3/year) and grey (0.64 Gm^3/year). China was the largest importer from Thailand followed by Indonesia, Taiwan, Malaysia and Japan. In addition, the product imported to Thailand and Lao PDR was the largest cassava starch source (0.65 Mm^3/year), followed by Thailand (0.48 Mm^3/year) and Myanmar (0.33 Mm^3/year), respectively.

5.1.2 Water footprint and virtual water flow of trade refined sugar

In the first part, the CWU_{eva} and WF_{eva} of sugarcane cultivation was calculated. It shows that the ET results under the CWR-option (option 1) were slightly higher than under the irrigation schedule-option (option 2) for the same reason as mentioned for the cassava cultivation, namely, that the crops were grown under non-standard conditions, and the soil conditions and soil water stress affected the crop transpiration that made the ET_a low in option 2. Nevertheless, the results of both options showed that the amount of green and blue components was quite different as they were affected by the climate and soil conditions under which each crop was grown. The CWU_{eva} and WF_{eva} found that largest region was the Northeast, followed by the Central Plain and Northern regions, respectively. The components of the WF revealed that the green component was larger than the blue and grey. The estimation under the CWR-option found that the average CWU_{eva} for whole country was about 11,798 m^3/ha, consisting of CWU_{green} (6,774 m^3/ha) and CWU_{blue} (5,024 m^3/ha), while the WF_{eva} for the whole country was estimated at about 161 m^3/ton, comprising the WF_{green} (92 m^3/ton) and the WF_{blue} (69 m^3/ton). On the other hand, the estimate of CWU_{eva} under the irrigation schedule-option was about 11,766 m^3/ha, consisting of CWU_{green} (7,547 m^3/ha) and CWU_{blue} (4,219 m^3/ha), whereas the WF_{eva} for the whole country was estimated at about 161 m^3/ton, which comprised the WF_{green} (103 m^3/ton) and the WF_{blue} (58 m^3/ton). The assessments of the WF_{grey} was found to be highest in the Northeastern region, followed by the Central Plain and Northern regions, which were around 36, 35 and 33 m^3/ton, respectively, and the average for the whole country was about 34 m^3/ton. Therefore, the WF_{total} of sugarcane cultivation, estimated under the irrigation schedule-option, was thus the summation of green, blue and grey components that were averaged for the whole country at 195 m^3/ton.

In the second part, information was collected about the amount of water consumption from one refined sugar factory in order to calculate the water mass flow balance per one ton of refined suger, and then to calculate the WF of the product. Moreover, the amount of water used in the refined sugar process from LCI data (data from previous studies of Thailand from the literature review) and the data of this study were used for weighting the average WF of refined sugar. The results for the WF of the sugarcane cultivation were obtained only under the irrigation schedule-option were used as the WF input to calculate the WF of the product. The results expressed the

WF_{total} of refined sugar production which was about 5,276 m^3/ton, consisting of green (2,783 m^3/ton), blue (1,571 m^3/ton) and grey (922 m^3/ton).

In the final part, the net VWF_{total} of refined sugar exports from Thailand were 13.88 Gm^3/year, composed of 7.32, 4.13 and 2.42 Gm^3/year of green, blue and grey components, respectively. With regard to the top five largest countries with VWF exports they accounted altogether for 45% including Cambodia, Indonesia, Iraq, Vietnam and India. This information show that the importer countries from Asia, especially South East Asia generally consumed the VWF of exports from Thailand. Furthermore, Thailand imports the virtual water more than 80% of its total imports from the UK (8.81 Mm^3/year).

With regard to the comprehensive amount of water use for cassava and sugarcane cultivation, for example, on an average basis in Thailand, it was observed that the required CWU_{eva} of cassava (9,051 m^3/ha) was lower than for sugarcane (11,766 m^3/ha), but the WF_{eva} shows the opposite trend, as cassava (528 m^3/ton) was higher than sugarcane (195 m^3/ton)., This can be explained by the fact that the yields of cassava (21 ton/ha) are lower than for sugarcane (70 ton/ha). Thus, it can be concluded that the large amound of yields is influenced by agricultural management rather than by the agro-climate in which the crops were grown.

Moreover, the planting dates, climatic and rainfall database, and soil characteristics are important data to establish a suitable cropping pattern for different locations so that water use can be saved and the supply of water will be sustained, especially for irrigation. In addition, the blue component (surface or groundwater) is mostly use in industrial processing, and is also required for the dilution of water pollution. The difference in volume of water use in the industrial sector depends on the policy of water saving, processing control and technology. The information about the VWF of trade products accounts for how much water was released from the country to support and save water consumption of importer countries that are facing water scarcity. The results of this study should be useful for water resources planning, management and policies to promote appropriate programmes for cropping, production and worldwide exports.

5.2 Recommendations

Based on the results of this study, the following recommendations are made in for further studies:

5.2.1 According to the first part of this study, focus needs to be based only on assessing the WF of cassava and sugarcane cultivation. For further study, major field and perennial crops are recommended for the assessment of WF in order to develop a database of Thailand's WF of agricultural crops.

5.2.2 The results in the agricultural sector should be used to determined the ideal cropping periods associated with the crop water requirements, yet in actual practice most Thai farmers crop using non-irrigated water. Water use should be calculated under rain-fed conditions to obtain a better understanding of how much water is actually used in the agricultural sector.

5.2.3 Only a few factories were selected for this research study as case studies for the data collection of the production process, so this information cannot be assumed to be representative of the whole country. Thus, more factories need to be selected as case that cover all the regions of Thailand and the data obtained needs to be based on statistical methods to obtain the most reliable results for their production processes.

5.2.4 The Thai government's policy on how much cassava starch and refined sugar productions and quantities of these commodities should be exported worldwide needs to be considered under a database of the WF and ecological footprints of agricultural crops in Thailand.

5.2.5 The results of this study can be used as a basis for future research and to provide suitable guidelines in future research, as regards the appropriate water management in the agricultural and industrial sectors of Thailand in order to improve productivity under the conditions of limited water use.

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APPENDICES

APPENDIX A

GEOGRAPHICAL DATA

Table A Geographical data of crop cultivation area in Thailand.

Provinces	Latitude (^{o}North)	Longitude (^{o}East)	Altitude (meter)
Northern			
Chiang Rai	19.57	99.52	410
Phayao	19.80	99.54	440
Lampang	18.16	99.31	268
Chiang Mai	18.47	98.58	310
Tak	16.52	99.80	116
Kampaeng Phet	16.29	99.32	107
Sukhothai	17.60	99.48	180
Phrae	18.10	100.1	155
Uttaradit	17.37	100.06	100
Phitsanulok	16.47	100.16	150
Phichit	16.26	100.17	168
Nakhon Sawan	15.48	100.10	150
Uthai Thani	15.20	100.03	100
Phetchabun	16.26	101.09	120
Northeastern			
Loei	17.27	101.40	180
Nong Bua Lam Phu	17.15	102.10	150
Udon Thani	17.23	102.48	165
Nong Khai	17.52	102.43	150
Sakon Nakhon	17.90	104.08	158
Nakhon Phanom	17.25	104.47	140
Mukdahan	16.32	104.43	160
Yasothon	15.47	104.08	128
Amnat Charoen	15.55	104.45	120
Ubon Ratchathani	11.15	104.52	140
Si Sa Ket	15.20	104.15	122
Surin	14.53	103.27	100
Buri Ram	15.13	103.14	150
Maha Sarakham	16.14	103.04	130
Roi Et	16.30	103.41	120
Kalasin	16.19	103.35	150
Khon Kaen	16.37	102.47	150
Chaiyaphum	15.48	102.02	180
Nakhon Ratchasima	14.57	102 04	180
Central plain			
Saraburi	14.36	100.58	150
Lop Buri	14.48	100.37	70
Sing Buri	14.35	100.20	16
Chai Nat	15.90	100.11	16
Suphan Buri	14.28	100.08	6
Ang Thong	14.35	100.27	6

Table A (Continued).

Provinces	Latitude (^{o}North)	Longitude (^{o}East)	Altitude (meter)
Prachin Buri	14.30	101.22	25
Chachoengsao	13.30	101.27	30
Sa Kaeo	13.47	102.02	74
Chantaburi	12.37	102.06	70
Rayong	12.37	101.20	50
Chon Buri	12.41	100.59	50
Nakhon Prathom	14.01	99.58	6
Kanchanaburi	14.10	99.32	150
Ratchaburi	13.29	99.47	7
Phetchaburi	12.59	100.03	5
Prachuap Khiri Khan	12.35	99.57	5

APPENDIX B

CLIMATIC DATA

Table B.1 The monthly average of climatic data in the Northern region of Thailand: 2008-2013.

Provinces	Month	Max temp. (^{o}C)	Min temp. (^{o}C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Chiang Rai	January	14.6	28.6	74	52	7.9	21.7
	February	15.7	31.5	68	60	8.4	9.9
	March	18.1	32.2	67	69	7.4	47.5
	April	21.7	34.3	68	80	8.0	85.4
	May	23.4	33.2	75	87	7.0	275.9
	June	24.2	32.2	78	87	5.3	193.5
	July	24.0	31.1	82	80	4.1	343.4
	August	23.8	30.9	83	71	4.5	400.4
	September	23.4	31.5	82	67	5.6	287.7
	October	22.0	30.9	80	63	6.3	152.7
	November	18.2	29.9	77	62	7.8	38.8
	December	15.0	27.7	76	48	7.1	21.2
Phayao	January	14.9	32.6	74.2	47.4	6.8	16.7
	February	17.0	35.0	67.7	55.6	7.6	7.8
	March	19.5	36.1	63.2	62.2	7.1	30.2
	April	23.4	38.0	64.5	74.1	7.6	71.3
	May	24.0	35.6	74.7	67.4	6.4	188.0
	June	24.2	34.3	75.7	101.5	5.4	109.0
	July	24.0	33.4	79.5	95.6	3.7	156.2
	August	23.6	33.1	82.0	64.4	3.8	189.0
	September	23.5	33.3	82.7	40.7	4.8	186.1
	October	22.1	32.4	83.2	24.4	5.5	132.8
	November	18.6	32.2	80.3	28.9	7.0	47.1
	December	15.4	30.4	79.0	34.8	7.2	12.5

Table B.1 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Lampang	January	16.1	31.6	71	10	6.8	14.2
	February	18.2	35.0	64	13	7.6	10.8
	March	20.5	36.1	61	18	7.1	42.1
	April	24.0	38.0	62	24	7.6	66.1
	May	24.4	35.6	74	16	6.4	224.2
	June	24.5	34.3	76	26	5.4	113.2
	July	24.2	33.4	78	22	3.7	137.3
	August	24.0	33.1	81	17	3.8	192.4
	September	23.7	33.3	83	10	4.8	206.4
	October	22.7	32.4	83	6	5.5	161.2
	November	19.6	32.2	78	7	7.0	15.3
	December	16.2	30.4	77	5	7.2	7.2
Chiang Mai	January	16.6	30.3	68	39	8.3	12.8
	February	18.0	33.6	59	42	9.0	7.7
	March	20.8	34.6	56	59	8.1	19.4
	April	24.2	36.5	58	80	8.4	54.8
	May	24.6	34.6	70	79	6.9	157.7
	June	24.8	33.2	73	76	5.1	120.4
	July	24.6	32.4	76	60	4.0	151.7
	August	24.2	31.9	79	50	4.0	252.3
	September	24.1	32.4	79	51	5.2	222.4
	October	23.2	31.8	77	51	6.1	142.4
	November	20.6	31.3	72	47	8.1	27.5
	December	17.4	29.1	72	34	7.8	8.2

Table B.1 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Tak	January	18.2	31.9	67	50	7.3	12.9
	February	20.9	35.5	57	70	8.7	8.1
	March	23.6	36.3	53	111	7.5	30.8
	April	26.2	37.6	57	160	8.0	71.8
	May	26.1	35.2	66	167	4.0	161.9
	June	25.6	33.0	73	159	3.5	132.5
	July	25.3	32.2	73	187	2.9	144.6
	August	25.2	32.2	73	183	2.9	105.5
	September	24.9	32.6	76	126	3.9	227.5
	October	23.8	31.8	81	45	5.2	238.8
	November	21.6	31.7	76	47	6.9	17.2
	December	18.2	30.4	73	47	7.4	6.9
Kampaeng Phet	January	19.5	31.2	72	30	7.3	4.7
	February	21.8	34.1	70	32	7.6	16.7
	March	22.9	35.0	68	34	6.9	50.3
	April	25.1	36.7	68	41	8.1	53.0
	May	25.3	35.1	78	38	7.1	190.3
	June	25.2	33.4	83	30	6.0	197.0
	July	24.8	32.5	84	27	4.4	237.4
	August	24.7	32.6	83	24	4.3	177.9
	September	24.6	32.6	85	25	4.6	307.4
	October	24.1	32.1	84	27	5.9	212.0
	November	22.3	32.1	78	27	7.4	20.3
	December	19.3	30.4	75	32	7.0	14.8

Table B.1 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Sukhothai	January	19.1	31.2	77	37	7.9	15.5
	February	21.2	33.6	76	53	7.8	6.3
	March	22.7	35.2	70	84	6.9	29.7
	April	25.4	37.6	68	122	8.0	82.4
	May	25.5	35.7	76	94	6.3	175.8
	June	25.2	34.0	79	106	5.5	186.0
	July	24.8	33.4	80	109	4.3	166.3
	August	24.6	32.8	80	79	3.7	191.5
	September	24.6	33.2	82	59	4.6	336.0
	October	24.2	32.8	82	47	5.5	230.2
	November	22.0	32.3	77	56	7.7	17.4
	December	19.1	30.4	78	41	7.8	17.0
Phrae	January	16.9	30.9	73	30	6.8	20.7
	February	19.2	33.7	69	40	7.6	6.9
	March	21.3	35.2	64	50	7.1	32.7
	April	24.8	37.3	64	60	7.6	99.9
	May	25.1	35.2	74	50	6.4	160.0
	June	25.0	33.5	77	60	5.4	180.2
	July	24.7	32.4	81	52	3.7	181.8
	August	24.5	32.0	83	36	3.8	222.8
	September	24.6	32.6	84	27	4.8	224.2
	October	23.7	32.2	82	22	5.5	65.7
	November	20.5	31.8	78	24	7.0	28.4
	December	16.9	30.0	76	25	7.2	11.7

Table B.1 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Uttaradit	January	19.1	32.1	67	6	7.9	8.1
	February	21.3	34.5	65	7	7.8	2.1
	March	22.8	35.4	63	12	6.9	34.2
	April	25.6	37.4	64	19	8.0	90.0
	May	25.8	36.2	72	14	6.3	170.5
	June	25.6	34.5	77	16	5.5	218.0
	July	25.2	33.5	79	2	4.3	200.2
	August	25.0	33.2	81	15	3.7	304.7
	September	25.0	33.6	81	8	4.6	242.5
	October	24.2	33.6	78	6	5.5	142.3
	November	22.0	33.4	71	6	7.7	12.4
	December	19.1	31.2	69	5	7.8	5.0
Phitsanulok	January	19.5	31.0	71	76	8.3	9.7
	February	21.9	33.6	70	81	8.7	12.4
	March	23.5	34.8	67	99	7.9	30.3
	April	25.4	36.7	65	117	8.8	60.6
	May	25.2	35.2	73	104	7.4	144.3
	June	24.8	33.8	78	106	6.3	168.9
	July	24.0	32.8	80	94	4.9	203.0
	August	24.3	32.4	81	89	4.4	263.1
	September	24.6	32.6	83	87	5.3	337.6
	October	24.2	32.4	81	80	6.1	155.4
	November	22.1	32.4	74	78	8.6	36.5
	December	19.2	30.5	73	79	8.4	13.9

Table B.1 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Phichit	January	18.9	30.8	77	22	7.1	15.5
	February	21.5	33.2	75	34	7.7	5.4
	March	22.9	34.2	72	45	7.1	32.8
	April	24.7	36.2	69	64	8.2	76.7
	May	24.8	35.0	75	67	7.3	118.7
	June	24.5	33.6	79	61	6.1	201.5
	July	24.1	32.6	82	45	4.4	215.2
	August	24.1	32.4	83	47	4.3	221.8
	September	24.3	32.0	84	42	4.6	367.3
	October	24.1	32.1	82	32	6.1	131.5
	November	22.0	32.1	78	37	7.3	27.9
	December	19.0	30.4	77	32	7.3	15.7
Nakhon Sawan	January	19.8	31.9	71	47	7.8	12.5
	February	23.1	35.0	68	63	8.1	9.2
	March	24.6	35.8	66	89	7.6	39.8
	April	26.1	37.5	67	84	8.0	77.0
	May	26.0	36.0	74	57	7.2	178.2
	June	25.6	34.5	77	69	5.7	131.8
	July	25.2	33.7	79	56	4.6	152.0
	August	25.1	33.6	80	47	4.5	194.6
	September	24.9	33.1	84	26	4.9	302.8
	October	24.5	32.6	83	21	6.2	239.1
	November	22.7	32.3	77	27	7.6	24.1
	December	19.6	31.1	73	36	8.2	5.2

Table B.1 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Uthai Thani	January	20.6	31.9	61	87	7.6	20.8
	February	23.1	34.5	65	66	8.1	15.5
	March	24.3	35.3	65	3	7.4	36.3
	April	25.6	36.9	68	4	8.0	74.3
	May	25.7	35.3	74	70	7.2	164.3
	June	25.1	33.8	78	69	6.1	141.8
	July	24.6	32.9	80	54	4.9	145.0
	August	24.5	32.8	81	48	4.4	205.4
	September	24.5	32.3	84	38	4.5	344.4
	October	23.9	32.1	80	53	6.1	199.8
	November	22.4	32.2	70	91	7.5	35.9
	December	20.2	31.1	64	107	7.8	4.8
Phetchabun	January	18.5	31.9	67	33	7.6	16.4
	February	20.9	34.8	66	31	8.1	17.7
	March	22.6	35.8	64	42	7.1	60.5
	April	24.6	37.4	67	39	7.3	76.1
	May	24.7	35.1	76	30	6.4	192.1
	June	24.4	33.9	79	35	4.9	124.4
	July	24.0	32.6	81	30	3.8	185.7
	August	24.0	32.2	84	19	3.4	201.7
	September	24.1	32.5	84	20	3.9	275.6
	October	23.2	32.7	80	27	5.7	93.2
	November	21.0	32.9	71	42	7.7	14.3
	December	18.0	31.4	69	32	6.9	11.9

Table B.2 The monthly average of climatic data in the Northeastern region of Thailand: 2008-2013.

Provinces	Month	Max temp. (°C)	Min temp. (°C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Loei	January	16.1	29.1	69	85	7.5	13.8
	February	18.2	32.8	64	89	8.4	12.5
	March	20.2	34.1	60	104	7.5	45.1
	April	23.1	35.6	66	98	7.7	119.6
	May	23.9	33.8	76	95	6.3	201.6
	June	24.4	33.0	76	90	5.2	135.7
	July	24.2	32.1	78	90	4.0	203.7
	August	24.1	31.8	79	96	4.2	258.9
	September	23.6	31.7	82	81	4.8	304.6
	October	22.4	31.2	80	0	5.8	126.2
	November	19.5	30.8	74	73	7.4	12.5
	December	15.9	28.7	72	77	7.6	22.0
Ning Bua Lam Phu	January	15.8	28.8	76	85	6.7	10.8
	February	18.0	32.5	71	89	7.5	13.0
	March	20.0	33.9	68	104	6.9	48.4
	April	22.9	35.3	73	98	6.9	132.5
	May	23.7	33.6	83	95	5.6	165.1
	June	24.1	33.0	82	90	4.3	124.3
	July	23.9	32.0	85	90	3.2	186.3
	August	23.6	31.9	86	96	3.5	171.7
	September	23.4	31.7	88	81	4.2	293.9
	October	22.1	30.9	86	0	5.0	128.7
	November	19.1	30.5	81	73	6.4	11.6
	December	15.6	28.4	79	77	6.6	16.1

Table B.2 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Udon Thani	January	16.5	29.4	67	110	6.7	14.0
	February	19.0	32.7	63	101	7.5	15.2
	March	21.3	34.3	60	123	6.9	40.2
	April	24.3	36.3	62	118	6.9	75.8
	May	24.7	34.5	73	108	5.6	209.8
	June	25.1	33.2	76	118	4.3	186.2
	July	24.9	32.4	79	111	3.2	244.8
	August	24.5	32.1	80	110	3.5	272.8
	September	24.4	32.2	81	96	4.2	249.3
	October	23.2	32.1	75	0	5.0	91.3
	November	20.2	31.6	67	97	6.4	36.4
	December	16.6	29.2	67	100	6.6	10.2
Nong Khai	January	17.4	29.3	68	115	7.5	19.5
	February	19.9	32.2	65	112	8.4	14.8
	March	21.8	33.8	63	118	7.5	70.1
	April	24.5	36.1	65	122	7.7	72.7
	May	24.8	34.4	76	107	6.3	268.0
	June	25.0	33.2	80	95	5.2	255.0
	July	24.9	32.4	83	90	4.0	365.9
	August	24.6	32.2	83	91	4.2	364.9
	September	24.6	32.5	81	93	4.8	300.9
	October	23.6	32.4	75	0	5.8	96.8
	November	21.0	31.6	68	112	7.4	37.3
	December	17.5	29.4	68	114	7.6	11.3

Table B.2 (Continued).

Provinces	Month	Max temp. (°C)	Min temp. (°C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Sakhon Nakhon	January	16.6	28.6	67	77	8.2	15.6
	February	19.3	31.9	63	81	8.5	11.3
	March	21.9	33.6	61	81	7.9	57.3
	April	24.6	35.0	66	65	8.0	154.3
	May	25.2	33.4	76	45	6.4	247.9
	June	25.6	32.7	79	53	5.1	246.3
	July	25.2	32.0	81	55	4.6	365.6
	August	24.9	31.6	82	53	4.6	339.1
	September	24.8	31.7	82	39	5.0	237.7
	October	23.1	31.5	75	54	7.2	81.4
	November	20.5	31.1	69	63	8.2	10.1
	December	16.9	28.8	68	64	8.3	10.0
Nakhon Phanom	January	16.7	28.7	68	107	7.8	6.6
	February	19.4	31.8	66	94	8.1	14.3
	March	22.2	33.3	65	102	7.0	56.2
	April	24.5	34.7	70	76	7.1	99.1
	May	24.9	33.1	80	61	5.6	335.5
	June	25.3	32.1	82	44	4.5	369.8
	July	24.8	31.3	85	42	4.3	582.9
	August	24.7	31.3	86	41	4.1	480.8
	September	24.5	31.7	83	45	4.2	267.5
	October	22.8	32.0	75	64	6.5	75.8
	November	20.5	31.5	68	87	7.9	3.3
	December	16.9	29.1	67	98	8.1	6.1

Table B.2 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Mukdahan	January	17.0	29.6	66	116	7.8	3.3
	February	19.7	33.1	61	92	8.1	2.9
	March	22.4	34.5	59	101	7.0	39.6
	April	24.8	35.8	64	73	7.1	76.8
	May	25.2	34.4	74	53	5.6	241.6
	June	25.4	33.6	77	53	4.5	246.7
	July	25.0	32.9	79	47	4.3	248.4
	August	24.8	32.1	82	41	4.1	319.8
	September	24.5	32.2	82	40	4.2	215.6
	October	22.9	32.0	74	76	6.5	73.5
	November	20.8	31.3	69	107	7.9	14.0
	December	17.5	29.3	68	109	8.1	6.6
Yasothon	January	17.2	29.7	69	179	8.4	18.0
	February	19.8	32.7	67	136	8.7	8.4
	March	21.9	34.2	66	155	7.7	32.1
	April	24.4	35.6	69	125	7.9	77.8
	May	24.8	34.1	78	121	7.0	186.7
	June	25.1	33.1	79	166	6.4	127.3
	July	24.7	32.2	81	161	5.8	210.9
	August	24.8	31.6	83	136	5.0	252.9
	September	24.6	31.1	86	91	4.7	304.2
	October	23.2	31.0	80	130	7.5	118.6
	November	20.6	30.9	74	185	8.2	16.4
	December	17.4	29.5	71	189	8.7	3.6

Table B.2 (Continued).

Provinces	Month	Max temp. (^{o}C)	Min temp. (^{o}C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Amnat Charoen	January	17.1	31.7	67	104	8.4	4.3
	February	19.4	34.5	65	71	8.4	7.4
	March	21.4	35.6	63	87	7.3	37.2
	April	23.9	36.3	69	65	7.0	93.9
	May	24.2	34.3	78	64	6.4	208.6
	June	24.4	33.5	79	73	5.5	160.8
	July	24.0	32.7	81	68	5.1	269.6
	August	23.9	32.0	84	51	3.8	314.2
	September	23.7	31.6	85	47	3.7	377.6
	October	22.5	32.3	79	71	6.0	101.4
	November	20.7	32.3	72	130	7.4	11.1
	December	17.6	31.2	69	118	8.0	11.2
Ubon Ratchathani	January	17.8	31.7	65	178	8.3	6.3
	February	20.3	34.4	62	141	8.7	3.0
	March	21.9	35.5	60	160	8.0	29.7
	April	23.6	36.3	66	139	7.8	87.5
	May	24.0	34.6	75	130	5.7	234.8
	June	24.8	33.8	76	158	5.3	162.7
	July	24.4	32.9	78	170	5.6	308.4
	August	24.2	32.3	81	158	4.2	349.8
	September	23.9	31.8	83	141	4.0	383.4
	October	22.7	32.3	76	146	6.4	111.9
	November	21.2	32.4	70	199	7.5	28.8
	December	18.4	31.1	68	182	8.0	18.5

Table B.2 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Si Sa Ket	January	17.8	30.7	69	70	8.4	4.3
	February	20.2	33.8	67	44	8.9	3.9
	March	22.1	35.0	65	61	8.1	16.4
	April	24.7	36.1	70	44	7.9	107.5
	May	25.2	34.5	77	41	7.2	227.6
	June	25.5	33.6	78	59	7.0	123.9
	July	24.9	32.7	80	50	6.2	223.1
	August	24.8	32.1	82	42	5.2	220.6
	September	24.5	31.3	85	25	4.6	350.0
	October	23.8	31.4	79	50	7.3	134.6
	November	21.8	31.4	72	105	8.0	23.8
	December	18.4	29.9	70	84	8.2	8.0
Surin	January	18.5	30.6	65	127	6.9	5.5
	February	21.3	33.6	62	107	7.4	15.8
	March	23.1	34.8	61	122	7.2	40.0
	April	25.2	35.9	66	115	7.1	89.4
	May	25.4	34.4	75	104	6.2	205.0
	June	25.2	33.5	77	121	6.0	164.2
	July	24.8	32.8	78	118	5.4	200.1
	August	24.6	32.3	80	107	3.7	233.7
	September	24.4	31.6	83	91	3.9	350.2
	October	23.6	31.5	79	108	6.1	128.3
	November	21.5	31.7	71	140	6.0	33.2
	December	18.6	30.1	67	141	6.2	4.8

Table B.2 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Buri Ram	January	17.3	30.4	67	115	6.9	16.2
	February	20.2	33.7	63	106	7.4	11.7
	March	22.3	35.3	61	117	7.2	36.2
	April	24.4	36.3	68	105	7.1	86.2
	May	24.6	34.7	77	95	6.2	205.0
	June	24.4	33.9	79	112	6.0	150.8
	July	23.9	33.2	80	122	5.4	191.5
	August	23.9	32.5	83	106	3.7	297.4
	September	23.6	31.9	86	66	3.9	276.0
	October	22.5	31.6	82	71	6.1	114.6
	November	20.3	31.3	75	97	6.0	21.9
	December	17.1	29.9	71	93	6.2	1.9
Maha Sarakham	January	17.4	30.4	71	123	8.4	18.8
	February	20.2	33.2	67	106	8.7	12.6
	March	22.3	34.6	66	107	7.7	33.0
	April	24.7	36.2	68	97	7.9	96.5
	May	25.0	35.2	76	87	7.0	204.4
	June	25.1	34.4	75	123	6.4	96.5
	July	24.7	33.6	78	113	5.8	225.2
	August	24.5	32.9	81	109	5.0	251.2
	September	24.4	32.6	83	70	4.7	309.0
	October	23.4	32.4	79	83	7.5	81.2
	November	21.0	32.1	72	109	8.2	26.5
	December	17.6	30.5	71	107	8.7	4.0

Table B.2 (Continued).

Provinces	Month	Max temp. (°C)	Min temp. (°C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Roi Et	January	17.5	29.7	67	128	8.3	17.9
	February	20.2	32.8	65	105	9.1	6.5
	March	22.5	34.2	63	116	7.8	35.7
	April	25.0	35.9	66	99	8.0	67.5
	May	25.3	34.6	75	100	7.2	204.8
	June	25.6	33.7	75	143	6.2	140.1
	July	25.2	32.8	77	139	5.3	198.4
	August	25.0	32.1	80	127	5.0	260.2
	September	24.8	31.6	83	81	4.6	309.7
	October	23.4	31.3	77	105	7.5	99.4
	November	21.1	31.2	70	138	8.4	17.0
	December	18.0	29.5	67	139	8.6	3.7
Kalasin	January	17.3	29.2	64	232	7.2	20.6
	February	20.0	32.2	63	199	7.6	9.7
	March	22.1	33.7	61	212	7.1	25.8
	April	24.4	35.7	64	189	7.1	71.7
	May	25.1	34.5	71	199	5.6	161.3
	June	25.4	33.4	74	173	4.6	185.5
	July	25.0	32.5	77	161	4.2	203.1
	August	24.8	31.8	81	154	4.0	272.2
	September	24.7	31.5	83	120	4.2	262.9
	October	23.2	31.2	75	168	6.3	75.4
	November	20.5	30.7	68	209	7.1	14.5
	December	17.1	29.2	65	219	7.2	6.6

Table B.2 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Khon Kaen	January	17.8	29.8	63	179	7.7	20.8
	February	20.3	32.8	61	159	8.2	4.2
	March	22.1	34.2	59	176	7.5	35.0
	April	24.6	35.9	64	147	7.2	119.1
	May	25.0	34.7	74	145	5.2	138.1
	June	25.1	33.9	74	178	3.9	116.3
	July	24.4	32.9	78	174	3.7	217.2
	August	24.1	32.3	80	164	4.1	224.6
	September	24.0	32.0	83	135	4.4	254.3
	October	23.1	31.7	75	163	6.5	76.2
	November	20.9	31.5	66	187	7.7	23.1
	December	17.9	29.8	63	190	7.7	5.4
Chaiyaphum	January	19.2	30.2	63	104	7.7	16.8
	February	21.5	33.6	59	84	8.2	5.5
	March	23.3	34.7	59	101	7.5	70.8
	April	25.1	36.0	64	84	7.2	93.8
	May	25.2	34.6	73	81	5.2	162.2
	June	25.2	33.4	74	107	3.9	118.4
	July	24.5	32.6	77	119	3.7	180.3
	August	24.2	31.9	79	101	4.1	267.6
	September	24.2	31.7	82	75	4.4	320.8
	October	23.6	31.3	76	89	6.5	135.3
	November	21.9	31.2	67	116	7.7	19.8
	December	19.0	29.7	64	112	7.7	11.9

Table B.2 (Continued).

Provinces	Month	Max temp. (°C)	Min temp. (°C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Naknon Ratchasima	January	19.3	30.0	69	119	7.0	20.3
	February	22.0	33.4	63	96	7.1	4.1
	March	23.5	34.6	64	105	6.6	54.5
	April	25.2	35.9	70	99	6.8	126.7
	May	25.7	35.0	75	105	6.3	136.1
	June	25.6	34.5	74	125	5.3	86.5
	July	25.1	33.8	75	127	4.2	174.4
	August	24.9	33.1	79	113	4.1	165.5
	September	24.5	32.0	83	87	3.9	268.9
	October	24.0	31.2	80	111	5.2	193.4
	November	22.2	30.9	72	147	6.2	26.4
	December	19.2	29.5	68	129	7.3	0.4

Table B.3 The monthly average of climatic data in the Central Plain of Thailand: 2008-2013.

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Saraburi	January	18.8	31.7	66	129	7.6	22.7
	February	21.4	34.9	65	107	7.9	6.8
	March	23.0	35.8	64	119	6.9	34.6
	April	24.6	37.0	69	87	7.6	99.4
	May	25.0	35.5	76	78	6.8	133.6
	June	24.7	34.8	77	85	5.3	101.0
	July	24.2	33.9	79	76	4.2	108.1
	August	24.1	33.7	81	60	3.9	205.8
	September	23.9	32.8	85	46	4.2	315.1
	October	23.4	32.5	81	66	5.5	200.5
	November	21.2	32.2	73	98	7.5	5.4
	December	18.1	31.2	69	117	8.1	4.2
Lop Buri	January	21.7	32.3	64	91	7.6	22.7
	February	24.2	34.2	69	70	7.9	6.8
	March	25.1	35.0	68	99	6.9	34.6
	April	26.1	36.3	71	93	7.6	99.4
	May	26.3	35.4	73	90	6.8	133.6
	June	25.8	34.1	77	90	5.3	101.0
	July	25.3	33.3	79	79	4.2	108.1
	August	25.3	33.3	79	68	3.9	205.8
	September	25.2	32.7	82	54	4.2	315.1
	October	25.0	32.6	78	62	5.5	200.5
	November	23.8	32.7	67	110	7.5	5.4
	December	21.3	31.6	63	119	8.1	4.2

Table B.3 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Sing Buri	January	20.9	31.5	72	49	8.0	0.4
	February	23.5	34.2	74	41	7.9	1.7
	March	24.3	35.2	73	50	7.3	15.6
	April	25.5	37.1	72	47	8.1	33.6
	May	25.8	36.1	75	50	6.8	132.2
	June	25.4	34.5	77	57	4.3	92.0
	July	24.7	33.8	78	54	4.2	103.9
	August	24.5	34.1	78	47	4.7	119.3
	September	24.5	33.5	81	34	5.0	222.7
	October	24.4	32.6	80	41	6.1	190.6
	November	23.1	32.2	76	62	7.5	53.8
	December	20.3	30.8	72	67	8.2	3.1
Chai Nat	January	20.6	31.7	70	21	8.2	6.2
	February	23.2	33.7	73	25	8.4	5.5
	March	24.0	34.7	70	44	7.6	18.9
	April	25.7	36.8	68	53	8.7	45.3
	May	26.0	35.5	73	45	7.6	183.7
	June	25.6	34.0	76	55	5.9	167.3
	July	25.2	33.1	77	44	5.4	128.6
	August	25.1	33.1	78	45	5.0	152.9
	September	25.0	32.9	80	24	5.0	309.9
	October	25.0	32.5	79	19	6.2	215.8
	November	23.4	32.6	71	36	8.0	10.7
	December	20.3	31.2	70	39	8.5	3.0

Table B.3 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Suphan Buri	January	19.0	31.3	74	36	8.0	4.7
	February	21.7	34.0	74	30	7.9	17.6
	March	23.1	35.0	71	36	7.3	25.8
	April	24.5	36.8	68	37	8.1	45.0
	May	24.8	35.6	74	32	6.8	97.3
	June	24.3	34.1	76	42	4.3	111.2
	July	23.9	33.4	77	41	4.2	105.4
	August	23.9	33.8	77	41	4.7	119.6
	September	23.8	33.2	80	32	5.0	223.7
	October	23.2	32.4	82	19	6.1	197.3
	November	21.8	31.5	76	45	7.5	16.1
	December	18.9	30.4	73	41	8.2	7.9
Ang Thong	January	20.4	32.5	68	161	7.6	1.0
	February	23.1	34.4	72	98	7.9	11.4
	March	24.1	35.0	70	144	6.9	33.9
	April	25.2	36.3	73	107	7.6	66.4
	May	25.3	35.4	76	107	6.8	128.1
	June	24.6	34.1	78	101	5.3	125.2
	July	24.2	33.2	79	98	4.2	178.9
	August	24.0	33.2	80	93	3.9	201.1
	September	23.9	32.7	84	68	4.2	293.1
	October	23.5	32.7	81	91	5.5	121.5
	November	22.0	32.6	73	176	7.5	27.2
	December	20.0	31.9	67	212	8.1	5.6

Table B.3 (Continued).

Provinces	Month	Max temp. (°C)	Min temp. (°C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Prachin Buri	January	21.6	33.0	63	110	7.3	8.5
	February	23.9	35.0	68	66	7.2	17.3
	March	24.8	36.0	67	73	6.6	52.0
	April	25.7	36.7	72	63	6.8	98.1
	May	26.0	35.8	77	61	5.9	192.9
	June	25.6	34.3	81	51	5.0	283.3
	July	25.2	33.3	81	50	4.2	316.0
	August	25.2	33.3	81	47	4.5	395.6
	September	25.0	32.9	82	53	3.9	496.7
	October	25.0	33.0	77	82	5.6	152.1
	November	24.0	33.4	66	142	6.9	23.1
	December	21.6	32.5	62	142	7.9	1.1
Chachoengsao	January	19.9	32.7	68	69	7.3	26.0
	February	22.2	34.6	72	53	7.2	18.3
	March	23.0	34.7	75	70	6.6	97.5
	April	24.4	35.2	79	50	6.8	142.3
	May	24.9	34.3	82	49	5.9	167.4
	June	24.8	33.3	82	54	5.0	165.0
	July	24.4	32.4	83	56	4.2	235.2
	August	24.3	32.7	83	52	4.5	194.4
	September	24.1	32.0	86	44	3.9	370.9
	October	23.6	32.2	85	39	5.6	215.2
	November	21.9	32.1	77	66	6.9	27.9
	December	19.3	31.9	72	74	7.9	4.0

Table B.3 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Sa Kaeo	January	20.0	32.4	69	76	7.3	10.1
	February	22.7	34.5	71	61	7.2	34.6
	March	23.9	35.4	71	65	6.6	37.3
	April	25.2	36.1	76	55	6.8	122.5
	May	25.5	34.8	81	52	5.9	171.1
	June	25.2	33.5	84	41	5.0	202.6
	July	24.8	32.5	85	41	4.2	240.0
	August	24.8	32.5	86	41	4.5	238.5
	September	24.7	32.0	87	36	3.9	365.6
	October	24.5	32.3	84	39	5.6	204.5
	November	22.8	32.4	77	59	6.9	21.1
	December	19.8	31.7	72	70	7.9	1.7
Chantaburi	January	22.3	32.4	66	124	6.9	33.6
	February	23.9	32.8	75	72	6.5	61.7
	March	24.4	33.2	75	76	6.5	104.8
	April	25.2	34.0	78	55	6.4	164.7
	May	25.4	33.2	82	54	4.6	443.1
	June	25.6	32.2	83	73	4.0	432.2
	July	25.1	31.5	84	70	3.3	593.1
	August	25.1	31.9	83	70	3.6	402.3
	September	24.7	31.5	85	50	3.0	588.0
	October	24.3	32.2	82	71	4.5	279.7
	November	23.7	32.5	72	153	6.5	68.5
	December	22.0	32.0	65	161	7.2	5.2

Table B.3 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Rayong	January	22.4	30.6	73	78	7.9	44.4
	February	25.2	31.0	78	108	8.0	38.7
	March	26.1	31.5	77	96	7.5	64.6
	April	27.1	32.6	77	101	7.9	83.1
	May	27.5	32.2	78	152	5.8	177.2
	June	27.3	31.3	79	238	5.2	185.5
	July	26.8	30.8	79	205	4.6	251.5
	August	26.5	30.9	80	180	5.0	182.4
	September	25.9	30.7	81	143	4.0	291.0
	October	24.8	31.1	83	67	5.7	213.7
	November	24.0	31.8	74	76	7.4	34.4
	December	22.0	31.1	71	73	8.5	2.3
Chon Buri	January	22.8	32.3	66	93	8.1	20.3
	February	24.9	33.3	72	75	7.7	21.3
	March	25.6	33.9	71	78	7.2	69.0
	April	26.7	34.8	72	65	7.9	90.8
	May	26.9	34.6	73	62	6.6	134.3
	June	26.8	33.9	73	73	5.6	132.0
	July	26.4	33.2	74	68	4.7	187.5
	August	26.1	33.2	75	65	7.0	229.3
	September	25.6	32.7	79	53	4.2	331.7
	October	25.1	32.8	78	59	5.1	239.3
	November	24.3	33.0	69	104	6.1	45.0
	December	22.5	32.4	64	107	7.9	6.1

Table B.3 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Nakhon Pathom	January	19.8	31.1	75	64	7.8	1.8
	February	22.5	34.0	76	62	8.1	12.8
	March	23.4	34.7	74	87	7.5	16.1
	April	24.4	36.2	74	88	8.3	62.0
	May	24.4	35.5	77	83	7.2	134.7
	June	24.4	34.1	80	77	5.5	146.4
	July	24.1	33.4	80	90	4.7	95.7
	August	24.2	33.7	80	98	5.0	125.7
	September	24.0	33.1	83	84	5.2	245.9
	October	23.5	32.1	84	67	6.1	243.7
	November	22.2	31.2	79	94	7.1	40.0
	December	19.5	30.0	77	78	7.5	2.2
Kanchanaburi	January	19.7	32.7	64	13	8.0	2.9
	February	22.4	35.4	65	16	7.9	35.1
	March	23.2	36.0	64	16	7.3	85.1
	April	24.6	37.3	65	14	8.1	44.0
	May	24.9	36.0	70	8	6.8	144.9
	June	24.4	34.4	74	4	4.3	119.2
	July	23.9	33.6	74	5	4.2	126.7
	August	24.1	33.8	74	11	4.7	117.1
	September	23.9	33.4	77	7	5.0	242.7
	October	23.3	32.4	80	4	6.1	205.1
	November	21.9	31.9	72	13	7.5	54.8
	December	19.3	31.4	67	11	8.2	2.4

Table B.3 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Ratchaburi	January	20.7	31.6	71	126	7.5	3.2
	February	22.7	34.1	73	113	7.9	8.6
	March	23.7	34.6	74	131	7.2	42.5
	April	25.2	35.9	73	125	7.8	33.6
	May	25.7	34.9	78	99	6.0	123.6
	June	25.3	33.5	80	99	4.7	117.2
	July	24.9	32.8	81	96	3.9	162.1
	August	24.9	32.9	80	113	4.2	118.7
	September	24.8	32.4	83	107	4.0	181.2
	October	24.5	31.5	86	103	4.7	233.7
	November	23.2	30.8	80	147	6.3	68.6
	December	20.7	30.3	73	160	7.5	6.9
Phetchaburi	January	22.0	30.4	73	193	7.5	25.1
	February	24.2	31.9	76	238	7.9	3.9
	March	24.9	32.6	75	287	7.2	49.8
	April	25.9	34.0	75	247	7.8	44.2
	May	26.4	34.1	74	187	6.0	106.4
	June	26.1	33.5	75	179	4.7	80.8
	July	25.5	33.0	75	158	3.9	95.7
	August	25.7	33.1	75	161	4.2	94.3
	September	25.3	32.9	77	133	4.0	115.2
	October	24.6	31.9	81	136	4.7	317.6
	November	23.7	31.6	75	207	6.3	82.6
	December	21.6	30.6	70	220	7.5	3.6

Table B.3 (Continued).

Provinces	Month	Max temp. (ºC)	Min temp. (ºC)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Total rain (mm)
Prachuap Khiri Khan	January	21.7	31.3	73	98	6.0	38.0
	February	22.8	32.7	77	89	7.5	27.4
	March	23.6	33.5	76	103	7.7	76.2
	April	25.1	34.7	76	87	7.5	59.5
	May	25.8	34.6	76	73	6.3	72.5
	June	25.6	33.3	76	82	4.7	96.0
	July	24.9	32.7	77	79	4.4	145.6
	August	25.2	33.2	75	80	4.9	54.4
	September	24.8	32.8	77	75	4.5	111.3
	October	24.1	32.3	81	46	5.3	173.9
	November	23.7	31.6	75	113	5.2	120.1
	December	22.0	31.1	70	121	5.9	18.9

APPENDIX C

SOIL DATA

Table C Soil data and their associated data input in CROPWAT 8.0 program and the initial available soil moisture by province of Thailand.

Provinces	Soil series	Soil types	Total available soil moisture (mm/m)	Maximum rain infiltration (mm/day)	Initial available soil moisture (mm/m)
Northern					
Chiang Rai	29	clay	215.9	24	126.0
Phayao	35	loam	229.2	240	114.6
Lampang	35	loam	229.2	240	114.6
Chiang Mai	35	loam	229.2	240	114.6
Tak	46	clay	116.0	24	58.0
Kampaeng Phet	33	sandy loam	250.6	480	125.3
Sukhothai	33	sandy loam	250.6	480	125.3
Phrae	33	sandy loam	250.6	480	125.3
Uttaradit	35	loam	229.2	240	114.6
Phitsanulok	35	loam	229.2	240	114.6
Phichit	33	sandy loam	250.6	480	125.3
Nakhon Sawan	35	loam	229.2	240	114.6
Uthai Thani	40	sandy loam	135.7	480	67.8
Phetchabun	54	clay	223.8	24	111.9
Northeastern					
Loei	35	loam	229.2	240	114.6
Nong Bua Lam Phu	35	loam	229.2	240	114.6
Udon Thani	35	loam	229.2	240	114.6
Nong Khai	40	sandy loam	135.7	480	67.8
Sakon Nakhon	35	loam	229.2	240	114.6
Nakhon Phanom	40	sandy loam	135.7	480	67.8
Mukdahan	35	loam	229.2	240	114.6
Yasothon	35	loam	229.2	240	114.6
Amnat Charoen	41	sand	56.6	480	28.3
Ubon Ratchathani	40	sandy loam	135.7	480	67.8
Si Sa Ket	40	sandy loam	135.7	480	67.8
Surin	40	sandy loam	135.7	480	67.8
Buri Ram	40	sandy loam	135.7	480	67.8
Maha Sarakham	35	loam	229.2	240	114.6
Roi Et	40	sandy loam	135.7	480	67.8
Kalasin	35	loam	229.2	240	114.6
Khon Kaen	36	loam	229.2	240	114.6
Chaiyaphum	40	sandy loam	135.7	480	67.8
Nakhon Ratchasima	40	sandy loam	135.7	480	67.8

Table C (Continued).

Provinces	Soil series	Soil types	Total available soil moisture (mm/m)	Maximum rain infiltration (mm/day)	Initial available soil moisture (mm/m)
Central plain					
Saraburi	52	clay	223.9	24	111.9
Lop Buri	52	clay	223.9	24	111.9
Sing Buri	33	sandy loam	250.6	480	125.3
Chai Nat	44	sand	56.6	480	28.3
Suphan Buri	33	sandy loam	250.6	480	125.3
Ang Thong	33	sandy loam	250.6	480	125.3
Prachin Buri	46	clay	116.0	24	58.0
Chachoengsao	46	clay	116.0	24	58.0
Sa Kaeo	35	loam	229.2	240	114.6
Chantaburi	45	clay	116.0	24	58.0
Rayong	35	loam	229.2	240	114.6
Chon Buri	35	loam	229.2	240	114.6
Nakhon Prathom	33	sandy loam	250.6	480	125.3
Kanchanaburi	33	sandy loam	250.6	480	125.3
Ratchaburi	40	sandy loam	135.7	480	67.8
Phetchaburi	33	sandy loam	250.6	480	125.3
Prachuap Khiri Khan	35	loam	229.2	240	114.6

CURRICULUM VITAE

Name	Ms. Manuswee Phanichnok
Date of birth	January 21, 1983
Place of birth	Nakhon Ratchasima province, Thailand
Education	
2002-2006	B.Sc. (Environmental Health) - Suranaree University of Technology, Thailand.
2006-2009	M.P.H. (Environmental Health) - Khon Kaen University, Thailand.
2010-2015	B.P.H. (Occupational Health and Safety) - Sukhothai Thammathirat Open University, Thailand.