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THESIS

# WATER USAGE IN RELATION TO WATER AVAILABILITY FOR CASSAVA STARCH PRODUCTION IN THAILAND

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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This work aims to develop a method to assess the impact of cassava starch production on local water resources by using water footprint (WF).This research applied WSI as a tool for accessing water scarcity in the Mae Klong, Tha Chin, Bang Pakong and Mun basin in Thailand. The WF calculation covered the water usage for both cassava fields (secondary data) and starch production at the factories (primary data). For the agricultural stage, only green water was considered as only actual water use rather than virtual water, was of interest. Blue water was not included because even though irrigation increases the yield of cassava roots, the costs usually exceed the additional revenue, making irrigation an uneconomic choice. Grey water was not included because the scenario of dilution of chemicals to acceptable levels is uncertain. The results showed that for all studied basins the total WF of cassava root production was 199ï306 $m^3$/t root, the difference of WF between basins can be explained by climatic conditions, soil characteristics, and starch content of the roots. The total water usage for cassava starch production ranged from 835ï1397$m^3$/t starch. Water was used mainly in the cassava processing 13.25ï36$m^3$/t starch. The water usage for cassava starch production corresponded to 44ï54% of the water availability (rainfall) in the river basins, which could be considered as high. The WSI values obtained in this current work for all basins, except Mae Klong basin was higher than 0.4, which was also higher than literature for Thailand. It is the threshold for severe water stress according to Pfister *et al*. (2009).

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# LIST OF ABBREVIATIONS

COD = Chemical oxygen demand
CWU = Crop water usage
DAO = Department of Agriculture
EEA. = European Environment Agency
EPA = Environmental Protection Agency
$ET_0$ = Evapotranspiration
$ET_c$ = Evapotranspiration
FAO = Food and Agriculture Organization
ISO = International Organization for Standardization
$K_{c\ end}$ = the Crop coefficients for the end
$K_{c\ ini}$ = the Crop coefficients for the beginning
$K_{c\ mid}$ = the Crop coefficients for the middle
$K_c$ = Crop coefficient
LCA = Life cycle assessment
LCI = Life cycle inventory
LCIA = Life cycle impact assessment
LDD = Land Development Department
lgp. = length of growing period in days
OAE = Office of Agricultural Economics
$P_{eff}$ = Effective rainfall
$Rain_{eff}$ = Effective rainfall
$s^*_{month}$ = Standard deviation of monthly
$s^*_{year}$ = Standard deviation of annual
TMD = Thai Meteorological Department
TTDI = Thai Tapioca Development Institute
TTSA = Thai Tapioca Starch Association
UASB = Upï flow Anaerobic Sludge Blanket
UNCTAD = United Nations Conference on Trade and Development
VF = Variation factor
WA = Water availability
WF = Water Footprint

# LIST OF ABBREVIATIONS (Continued)

$WF_{area}$ = Water Footprint calculated on a basin area basis
$WF_{blue}$ = Blue Water Footprint
$WF_{green}$ = Green Water Footprint
$WF_{grey}$ = Grey Water Footprint
$WF_{pop}$ = Water Footprint calculated on a population basis
$WF_{proc}$ = The total water footprint of the process
WSI = Water Stress Index
WTA = Withdrawal to Availability
$WTA^{*}$ = Withdrawal to Availability
WU = Water usage
Y = The crop yield

# WATER USAGE IN RELATION TO WATER AVAILABILITY FOR CASSAVA STARCH PRODUCTION IN THAILAND

## INTRODUCTION

Water scarcity is an increasing problem for several countries in the world, due to a variety of factors such as decreasing reserves of water, population growth, climate change, changing lifestyles, pollution from industrial development, and destructions of natural ecosystems. Freshwater represents less than 1% of the total volume of water in the world. Use of freshwater by human activities is allocated between agricultural, industrial and domestic uses, with 70%, 22% and 8% respectively (UNï Water Statistics, 2009). Thailand is a major consumer of water with about 2% of global water footprint. Most freshwater in Thailand is used by the agricultural sector (Hoekstra and Chapagain, 2007).

Cassava is a major industrial crop in Thailand, putting the country in the third place for production of cassava roots after Nigeria and Brazil, respectively, and in the first place for exports of cassava starch (UNCTAD, 2012). Cassava is the third economic crop of Thailand after rice and sugar cane, respectively (Sriroth *et al.*, 2000), with approximately 27 million tons of cassava roots produced in 2012. Cassava is currently planted in approximately 1.3 million *hectare* of land in 50 provinces (Office of Agricultural Economics [OAE], 2013). The Nakorn Ratchasima province is the largest cassava producing and processing region. Cassava starch production is carried out by 92 cassava processing plants operating 24 hours a day for 8ï 9 months, from September to May, with some plants operating year round. The production of cassava starch uses high amounts of energy, at approximately 2500MJ/ton starch (OAE, 2012; Chavalparit and Ongwandee, 2009) and water, in particular for the operations of root washing and starch separation. Water usage in cassava factory ranges from 10 to 30 $m^3$/ton starch (Thai Tapioca Starch Association [TTSA], 2004). In addition to water use during cassava starch production, the cultivation of cassava roots requires large amounts of water as well. To assess in details the water consumption of cassava starch production, Life Cycle Assessment (LCA) tools, Water Stress Index (WSI) approach and the Water Footprint (WF) approach can be used.

LCA tools are used to assess the interactions between human activities and environment. The principle of LCA is to analyze the impacts to the environment of goods or services from cradle to grave. A key step of LCA is the Life Cycle Inventory (LCI) to collect and validate data on all the inputs and outputs of the studied system, which is a prerequisite for WF calculations and WSI calculations.

The objective of this study is (1) to assess the water use and water stress for the production of cassava starch in four different basins, and (2) to investigate the methods to calculate water stress index (WSI) for Thailand.

# OBJECTIVES

1. To assess the water use and water stress for the production of cassava starch in four different basins

2. To investigate the methods to calculate water stress index (WSI) for Thailand

## Scopes of work

1. This research focuses on four sites of cassava starch factories in Central and Northeast Thailand, at Kanchanaburi, Ratchaburi, Nakhon Ratchasima and Chonburi in Tha Chin, Mae Klong, Mun and Bang Pakong basins.

2. Primary data were collected from factories in 2012ï 2013.

3. The secondary data including meteorological data (rainfall), runoff water, and water in reservoir cover monthly data over a 20 year period (1993ï 2012).

4. The water usage was calculated for agricultural sector and factory sector of cassava production and processing.

5. WSI Calculation use VF from the monthly average method.

6. WSI calculated from the concept of ratio of water used to water availability based on method developed by Pfister *et al*. (2009) and Ridoutt and Pfister (2010).

# LITERATURE REVIEW

## Theory

### 1. Cassava

Cassava is a plant species which the third largest source of carbohydrates in the world after rice and maize, respectively. Cassava is the fifth economic crop of the world after wheat, corn, rice and potatoes. Cassava is important crop in tropical countries, especially in Africa continent, South America and Asia continent; Indonesia and India consume high amount of cassava. The scientific name is *Manihot esculenta* (L.) Crantz. The cassava has many general names depend on region. Example, in Asia we call it Tapioca, South American it is called Madioca. (TTSA, 2004). Thailand does not have clearly evidence when cassava reached into Thailand, but presumed that the first of cassava bring to Thailand as same period as Sri Lanka and Philippine in 1786ï 1840 by imported from Malaysia. Cassava was first planted in south of Thailand; planted in rows between rubber trees. It was expanded in central plain and planted in northeastern, respectively.

#### 1.1 Components of cassava roots

Cassava roots are important part of tree. Cassava trees use roots to storage food. Fresh cassava roots consist water approximately 60ï 65%, starch or carbohydrate approximately 20ï 35% which is main nutrients storage in roots. The percentage of starch in cassava roots depend on duration of planted which in rainy season has percentage of starch in roots lower than in drought season. The starch contain in roots is decreases after harvested due to hydrolysis by microorganism. (Narinthapon *et al.*, 1979). Especially in tropical climate such as Thailand, the deterioration of cassava root appeared within 1ï 3 days after harvested and microorganism hydrolysis starch content cause cassava roots rotten within 5ï 7 days (Rickard and Gahan, 1983).

Cassava is energetic source of human and animals but contained less of protein and fat. Moreover, cassava contained Hydrocyanic acid which is poison to living creature, but it can be decreased after harvested and destroyed by heat. The chemical contents of fresh and dry cassava roots showed in Table 1.

**Table 1** Chemical contents of fresh and dry cassava roots

| Contents | Fresh cassava roots | Dry cassava roots |
|---|---|---|
| Moisture (%) | 63.25 | 10.63 |
| Carbohydrate (%) | 29.73 | 70.63 |
| Protein (%) | 1.18 | 2.63 |
| Fat (%) | 0.08 | 0.51 |
| Ash (%) | 0.85 | 2.20 |
| Fiber (%) | 0.99 | 1.73 |
| Potassium (mg/kg) | 0.26 | 0.43 |
| Phosphorus (mg/kg) | 0.04 | 0.08 |
| Hydrocyanic acid (ppm) | 173 | 100 |

**Source**: Department of Agriculture (2010)

### 1.2 Yield of cassava in Thailand

In 2011 to 2012, the planted area of cassava is approximately 1.3 million *hectare* of land in 50 provinces. The potential yield ranging 12 ï 23 ton/ha and average yield 20.2 ton of roots/ha see in Table 2 (OAE, 2012). Northeastern is the largest producing cassava area. Nakorn Ratchasima province is the largest cassava producing and processing region.

**Table 2** Area, production and yield by province of cassava. Period: 2011ï 2012

| Provinces | Average Planted area(ha) | Average harvested area(ha) | Average production (ton) | Average yield (ton/ha) |
|---|---|---|---|---|
| Country | 1260781 | 1200600 | 24256753 | 20.20 |
| Northern | 242819 | 228505 | 4694713 | 20.55 |
| Northeastern | 680694 | 653293 | 13074005 | 20.01 |
| Central Plain | 337269 | 318802 | 6488036 | 20.35 |
| Tak | 8724 | 8354 | 186098 | 22.28 |
| Uthai Thani | 24261 | 23696 | 476648 | 20.11 |
| Mukdahan | 22584 | 20522 | 396516 | 19.32 |
| Yasothon | 9425 | 9016 | 180509 | 20.02 |
| Amnat Charoen | 5652 | 5541 | 98978 | 17.86 |
| Ubon Ratchathani | 32135 | 31039 | 610376 | 19.67 |
| Buri Ram | 32905 | 32190 | 655237 | 20.36 |
| Maha Sarakham | 16000 | 15200 | 290451 | 19.11 |
| Roi Et | 8560 | 8241 | 160845 | 19.52 |
| Khon Kaen | 35162 | 34611 | 669435 | 19.34 |
| Chaiyaphum | 58844 | 57891 | 1166154 | 20.14 |
| Nakhon Ratchasima | 278152 | 270525 | 5468823 | 20.22 |
| Saraburi | 4954 | 4538 | 88437 | 19.49 |
| Chai Nat | 10778 | 10123 | 168493 | 16.64 |
| Suphan Buri | 4524 | 4328 | 81142 | 18.75 |
| Prachin Buri | 29392 | 27080 | 547919 | 20.23 |

**Source**: Office of Agricultural Economics (2012)

### 1.3 Characteristics of cassava in Thailand

Cassava planted in worldwide and Thailand consist two types which are Sweet cassava and Bitter cassava.

#### 1.3.1 Sweet cassava

Sweet cassava has low amount of hydrocyanic in cassava roots. It has tough , tender flesh and also not bitter. Sweet type used for human consumption. In Thailand, sweet cassava was unpopular planted because of low market demand. Therefore, it mostly planted for consumed in household and distribute in local market.

#### 1.3.2 Bitter cassva

Bitter cassava has high amount of hydrocyanic in casssava roots hence, it is highly toxic and bitter. This is suitable for consumption to human and animals feed, and also suitable to processing into products. There is a lot of types of cassava planted in Thailand. (TTSA,2004)

In the past, cassava was planted for commercial production called Rayoung 1 which contained low percentage of starch content thus, it make problems to agriculturist; low price due to low percentage of starch content in roots.

In 1997, the percentage of starch in roots is increased because agriculturist brought new varieties type of cassava to replace Rayong 1. Currently, Agriculture department and Kasetsart University have been collaborating to develop varieties of cassava for industry sectors and suggest varieties of cassava to agriculterists (Table 3).

**Table 3** Varieties of cassava roots in Thailand

| Varieties | Characteristics | Yield (ton of roots/ha) | starch of roots (%) |
|---|---|---|---|
| Rayong 1 | Tolerant to climate change and well growth in rich nutrient soils. | 25.63 | ï Rainy season 18.3%<br>ï Dry season 22ï 24% |
| Rayong 3 | Starch content in roots more than Rayong 1. It suitable for animal feed and cassava pellets industry. The characteristics are short tree and bunch of cassava roots hence, easy to dig cassava roots. | 24.38 | ï Rainy season23%<br>ï Dry season 22ï 24% |
| Rayong 60 | This type is well storage weight of fresh roots. It can harvest within 8 months and highest yield in 12 months | 8 month =19.38<br>12 month=26.25 | ï Rainy season18.3%<br>ï Dry season 26ï 28% |
| Rayong 90 | High yield of fresh roots and high percentage of starch content. Short time to kept stems but it is tolerant to leafï burnt disease. | 23.75 | ï Rainy season20%<br>ï Dry season 24% |
| Rayong 5 | High yield of fresh roots and moderate to high percentage of starch content. Tolerant during in the drought season. | 27.5 | ï Rainy season22.7%<br>ï Dry season 25ï 27% |

**Table 3** (Continued)

| **Varieties** | **Characteristics** | **Yield (ton of roots/ha)** | **starch of roots (%)** |
|---|---|---|---|
| Rayong 72 | High yield of fresh roots and stems have good quality but low starch content, if is planted in high ground water level area or heavy rainy area. | 31.88 | ï Rainy season20%<br>ï Dry season 22ï 24% |
| Kasetsart 50 | High yield of fresh roots and high percentage of starch content. Moreover, can be stored for a long term after cutting. This variety is more cultivated in Thailand. | 27.5 | ï Rainy season23%<br>ï Dry season 28% |
| Huay Bong 60 | Highest yield of fresh roots and high percentage of starch content in roots. Starch contains high viscosity hence, suitable to use in variety of industries. Stems are good quality which it can be stored for 15 to 30 days after cut and moderate tolerant to leafï burnt disease. | 31.25ï 53.9 | 25.5% |
| Huay Bong 80 | Huay Bong 80 has similar fresh root yield potential as Huay Bong 60, but has higher root starch content. Smaller plant and a few branches enable the plant to withstand higher plant population mechanization. | 31.03 | 27.6% |

**Source**: Department of Agriculterature (2012)

### 1.4 Soils and Fertilizer for cassava cultivation

Amount of starch in cassava roots which planted in varieties area are different, even thought is planted and harvested in same period. Mainly reasons that created the different are nutrient, humus and characteristic of soils. To increase starch in cassava, researcher experiment to put fertilizer in cassava fields. The results shown that cassava fields which put fertilizer affected cassava yield to increase, but percentage of starch decreased 1ï 2% because of increasing roots size effected moisture and starch content in roots decreased. (TTSA, 2004).

**Table 4** Average fertilizer application rate

| **Nutrients** | **Amount(kg/ha)** |
|---|---|
| Nitrogen (N) | 100 |
| Phosphorus (P) | 22 |
| Potassium (K) | 83 |

**Source:** FAO (2013)

### 1.5 Land preparation

Site selection to plant cassava should avoid area under chemical control for long period and should manage planting area such as contouring in slope land. Then, soils improvement by put an organic matter or plant foliage such as groundnuts and beans and thick sandy loam upland soils is ideal for cassava. If the soil is clay, drainage is necessary. For land preparation, you can add organic manure into soil to increase soil nutrients, improve soil structure and improve the ability of the soil to hold water.

### 1.7 Planting

Cutting up cassava stem should cut at least 20ï 25 cm long and has about 5ï 8 nodes from more than 8 months stems. The cutting stems will be soaking in (1:500 or 1: 1,000 dilution) LDD liquid organic fertilizer within 24 hours. They will be dried before planting. Vertical planting is best in sandy soils. Planting stem cut vertically with 2/3 of the length of the cutting below the soil. Agriculturists plant cassava in early rainy season (Marchï May) which accounted for more than 65% of whole cassava fields in Thailand, while 20% for planting in dry season (Novemberï February), and the remaining 13% is planted during June to October (Thailand Research fund, 2014). For Rayong 60 variety, 60*100 cm. spacing and from June to February growing period are recommended. For Kasetsart 50 variety, planting space of cassava should be 80ï 100 cm and recommended to plant from June. The planting in early rainy season leads to higher cassava root yield than the other season, except for the sand soil which is suitable for planting during dry season. Therefore, amount of rainfall, cassava species and characteristics of soils are taken into consideration for the appropriate time for planting cassava in Thailand (Thailand Research fund, 2014).

## 2 Cassava starch in Thailand

Cassava is a major industrial crop in Thailand, putting the country in the third place for production of cassava roots after Nigeria and Brazil, respectively, and in the first place for exports of cassava starch (UNCTAD, 2012). The world cassava production is 252 million tons (OAE, 2012). Cassava is the third economic crop of Thailand after rice and sugar cane, respectively (Sriroth *et al.*, 2000), with approximately 27 million tons of cassava roots produced in 2012. and approximately 50% of cassava roots is used as raw material for the production of Cassava starch which Thailand produced native and modified starch for export approximate 3 million tons of starch per year. (TTSA, 2004) Cassava starch production is carried out by 92 cassava processing plants operating 24 hours a day for 8ï 9 months, from September to May, with some plants operating year round. Quantity and quality of cassava roots depends on many factor such as type of cassava, soil temperature, rainfall, soil characteristic and fertilizer.

### 2.1 Current Problems in Thai Cassava Starch processing

Water is essential for agricultural industries especially washing root and extraction process. Like water, energy is crucial in starch drying process as machine requires energy consumption. As per this process, the machine consumed energy and transformed it to heat energy for drying the starch; this process is known as an energyï consuming process. Those are two natural resources that are known for a basis problem in arid areas. Aside from inefficiently consumed natural resources, another problem is starch loss which source of starch loss from starch production, in rasping process when mechanically rasped, some starch granules remain trapped inside the fibrous matrix. Moreover, starch is not recovered and discarded in the solid waste and starch lost in liquid phase after the separation process as high as 15% of starch content (Piyachomkwan *et al*., 2005).

### 2.2 Price of cassava starch

From statistic of cassava starch since 2005, the price of cassava starch continuously increased from about 220 US$/tons to about 500 US$/tons in 2009. The price is doubling from the original 2005. Then the stay constant in the range of 400ï 500 US$/tons until present (TTDI, 2012; TTSA, 2004)

### 2.3 Processing of cassava starch

Thailand cassava starch processing uses different technique and machine but main process maintains similar in every factories. One kilogram of cassava starch can be produced from 4.0 ï 4.4 kilograms of fresh cassava root. Cassava starch quantity depends on technology in processing. Processing of cassava started in roots preparation stage, weigh fresh cassava roots apparent density from roots weight in the air and in water to determine starch percentage. Soil and sand are removed as the roots through a cylindrical roots sieve and removed in roots washing process. Roots after sieving are transported into a water chamber to wash. Secondly, cleaning roots in the chopper and raspers, rasping until they becomes fine particles and sediment them in the water. In this step, they appeared as the slurry mix of starch, water, and fiber. Thirdly, pumped fresh rasped roots slurry from raspers through a series of extractors. Starch slurry exiting the coarse extractor contain amount of fine fiber which must be removed in the fine extractor and fine extraction is repeated with a finer screen aperture. Fourth, separated starch slurry from fine extraction and dewatering in a horizontal centrifuge. Finally, drying Starch cake which blown with hot air but this heatï moisture treatment can be problem to starch quality (Sriroth *et al.*, 2000). In addition, wastewater from whole processing is brought to generate biogas. In small to middle starch plants typically use a cover lagoon system to reclaim biogas from anaerobic ponds while large plants use upï flow anaerobic sludge blanket(UASB) .Some company use anaerobic fixedï film reactor because this system is reduced the construction area approximately oneï third and decreased odor surround the factory.

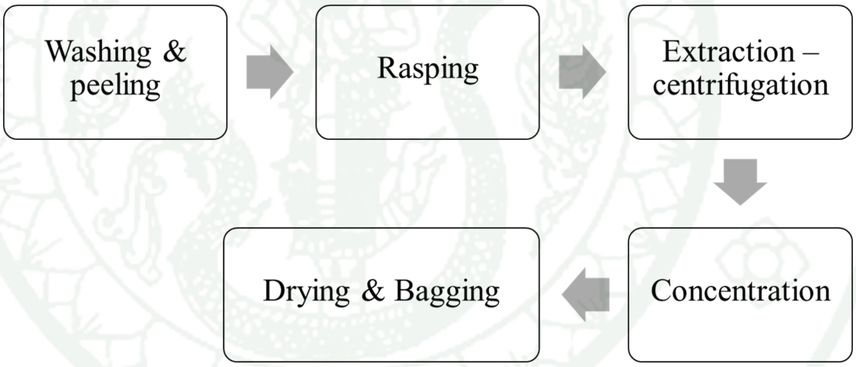

**Figure 1** Process of cassava starch production

**Source:** Chavalparit and Ongwandee (2008)

### 2.3.1 Root washing and peeling

Peeling is first step in cassava starch process after weight cassava roots process to measure starch content in cassava roots. Cassava roots are brought to cut bud and root tails before brought into cylindrical tank to peeling by using rotating and hitting of roots into machine. Rotating can remove sand and soil as well. Next step, cassava roots were sent to washing process. This process can removed sand and soil from cassava roots and cleaning cassava roots. Washing ponds have rotating paddles and interior pipe which sprays water on the roots. Water in this process has two sources; recycle water used in early pond and freshwater used in final pond.

### 2.3.2 Rasping

Rasping is one of process to rupture all cell walls in order to release the starch granules. Rasping machine is able to chopping roots and then rasping, grating or crushing them, which became slurry mix starch and fine pulp by pressing the roots with a swiftly moving surface provided with blade protrusion. The cell walls of cassava roots will be broke and some of the starch granules will release. The percentage of starch set free is called the rasping effect. Its value after one rasping may vary between 70 and 90 %: the efficiency of the rasping operation, therefore, it determines to a large extent the overall yield of starch in the processing. It is difficult to remove all the starch, even with efficient rasping devices, in a single operation. Therefore, the pulp is sometimes subjected to a second rasping process after screening. The rasping is carried out in different ways with varying efficiency.

### 2.3.3 Extraction

The slurry; consisting starch, fiber, water and impurities is obtained from rasping process and it is sent into the centrifuges for extraction of the starch from the fibrous residue. The extraction system consists of three or four centrifuges in series. There are two types of extractors: a coarse extractor with a perforated basket and a fine extractor with a filter cloth. This process add water and sulfur compounds for dilution and bleaching of the starch. The starch slurry is then separated into starch milk and fibrous residue. The coarse and fine pulp which remaining starch is passed to early extractor to reï extracted starch. The extracted pulp is sent to screw press for dewatering (Chavalparit and Ongwandee, 2008).

### 2.3.4 Concentration

Cassava production should process in short period of time because protect chemical reaction and enzyme reaction to effected amount and quality of starch in roots. Normally, Concentration process is continuous step and short duration time which starch is concentrated and sent to starch dewatering. Waste water from this process is high COD content which suitable to produce biogas.

### 2.3.5 Starch dewatering, drying and Bagging

The slurry starch is separated water and sent to flash dryer to evaporated moisture in starch by hot air in temperature 200□ and then the starch sent to cooling cyclone for decrease temperature and moisture. The final moisture content of starch is between 12ï 13%. Final process is bagging of starch (Chavalparit and Ongwandee, 2008).

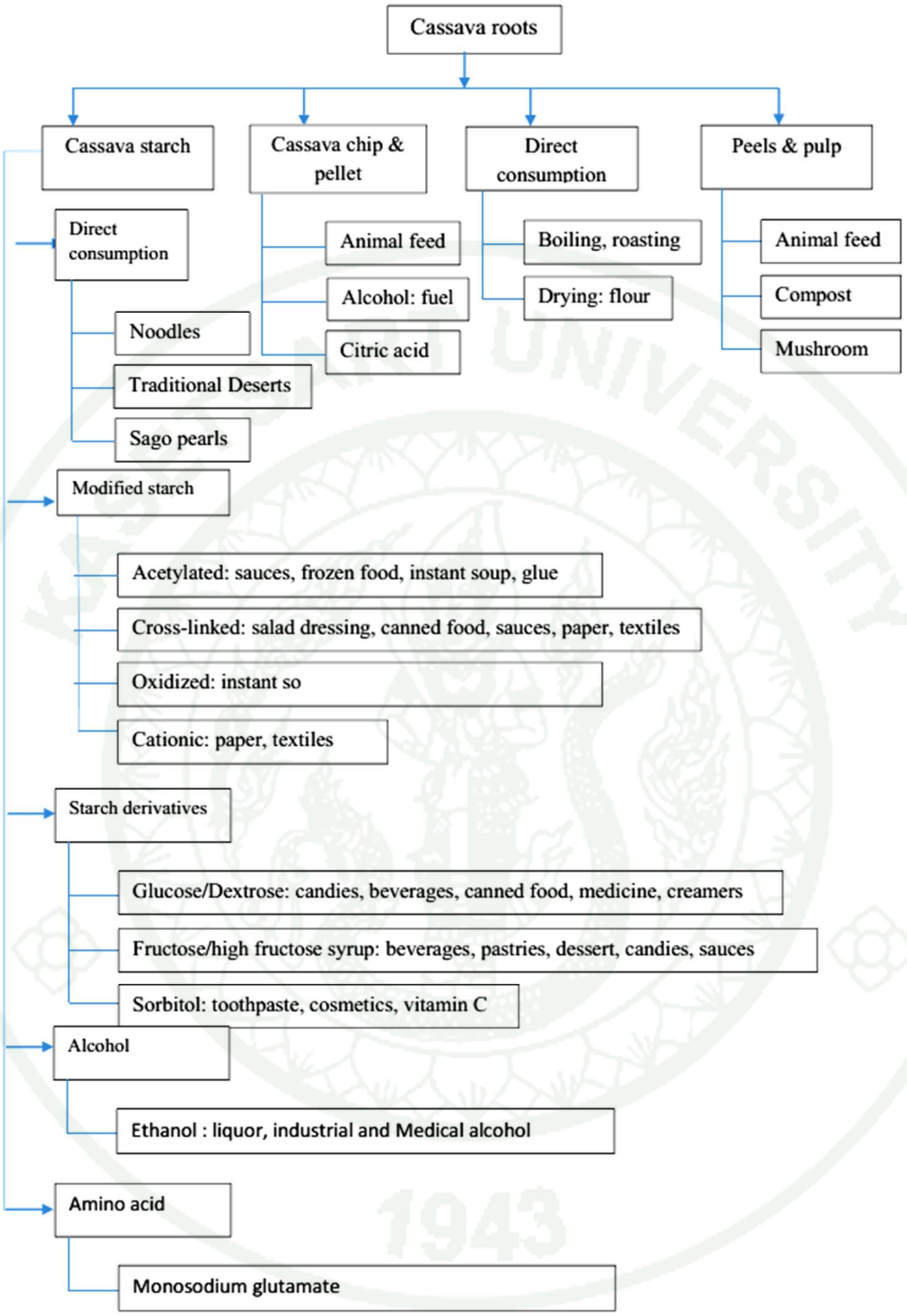

**Figure 2** Cassava products

**Source:** Thailand Research Fund [TRF]. 2014

### 3. Life Cycle Assessment (LCA)

LCA tools are used to assess the interactions between human activities and environment. The principle of LCA is to analyze the impacts to the environment of goods or services from cradle to grave. Concept of LCA is compilation and evaluation of inputs and outputs and the potential environmental impacts of a product system throughout its life cycle (ISO14040).

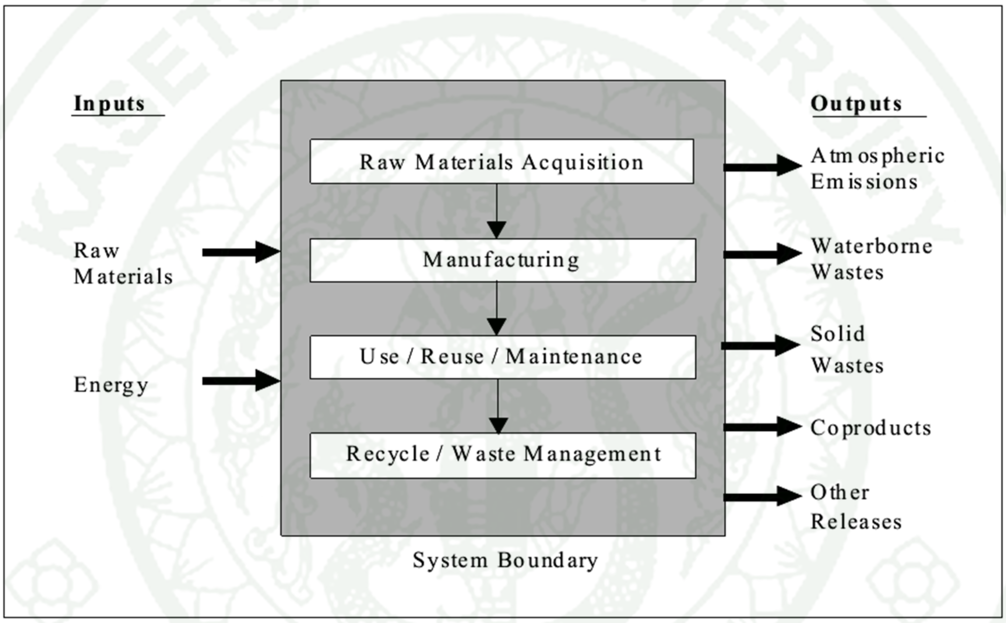

**Figure 3** Life cycle stage

**Source:** Environmental Protection Agency [EPA]. (1993)

The LCA process is systematic, phased approach and consists four components; goal definition and scoping, inventory analysis, impact assessment and interpretation which each components relative as well and explained in Figure 3.

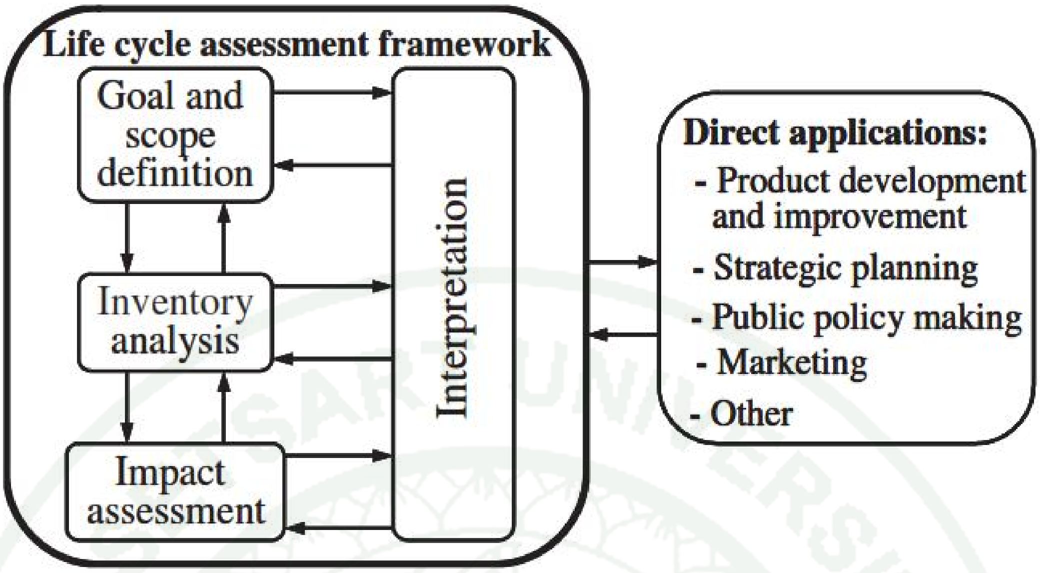

**Figure 4** Life cycle assessment framework and application

**Source:** International Organization for Standardization [ISO]. (1997)

3.1 Goal and Scope definition

This process in first phase of LCA process which defines the purpose, method of the study, boundary of the studies and identifies the necessary data for inventory and including environmental impact assessment. For determining the scope of the LCA, it must be consistent with the purpose.

3.2 Life cycle Inventory

Life Cycle Inventory (LCI) is phase to collect and validate data relevant within the studied system. The data obtained from the collection should cover all of the production process and all the inputs and outputs of the studied system.

3.3 Life cycle impact assessment phase (LCIA)

The Life Cycle Impact Assessment (LCIA) phase is the evaluation of potential human health and environmental impacts and releases identified during the

LCI. The results of an LCIA show the relative differences in potential environmental impacts for each option.

### 3.4 Interpretation

Life cycle interpretation is a systematic technique to identify and evaluate information from the results of the LCI and the LCIA, and communicate them effectively. Life cycle interpretation is the last phase of the LCA process. ISO has defined the objectives of life cycle interpretation to analysis results, reach conclusions, explain limitations, and provide recommendations based on results of the life cycle assessment of the study (ISO, 1998).

## 4 Water Footprint

Water Footprint is an indicator of fresh water use for human activities. The water footprint of a product or service is the volume of fresh water used during all the steps of the production chain (from cradle to grave as for the LCA approach). WF consists of three components: green water, blue water and gray water. (Hoekstra *et al.*, 2011).

### 4.1 Green water footprint ($WF_{green}$)

Green water refers to the precipitation on land that does not run off or recharge ground water, and is stored in the soils and plants. In other words, green water represents the fraction of precipitation that is eventually absorbed by plants and evaporated and transpired by agricultural crops through stomata and lenticel.

Green water footprint is the volume of water evaporated by agricultural crops through evapotranspiration.

### 4.2 Blue water footprint ($WF_{blue}$)

Blue water refers to the volume of surface water and ground water used during the production process: For agriculture blue water represents the irrigation needs when rainfall is not enough for the crop to grow under ideal conditions, and for industrial activities blue water represents the water used by factories in their production lines.

### 4.3 Grey water footprint ($WF_{grey}$)

Grey water refers to the volume of water required to dilute chemical or pollutants discharged to water bodies in order to maintain water quality according to agreed water quality standards (Hoekstra *et al*., 2011).

The unit of water footprint is $m^3$/ton of products which the water footprint of crops calculated from the volume of crop water use ($m^3$/ha)/yield of crops. The water footprint of animal is calculated from amount of water of all step in production and animal feed process, including drinking water for animal and water use for activity such as cleaning floor and cooling. The water footprint of production is the summation of water footprint in production process from crop and animal since the beginning process until finishing process.

The results of study in period 1996ï 2005 found that the global average water footprint is 1385 $m^3$/year/capita and that Thailand is a high water footprint country with 1407 $m^3$/person/year. Agricultural products are a large part of global water footprint, contributing 92% to the total water footprint. Industrial products and domestic water use contribute 4.7% and 3.8% respectively. The green, blue, grey and total water footprint per capita for all countries are presented in Figure 4 (Mekonnen and Hoekstra, 2011).

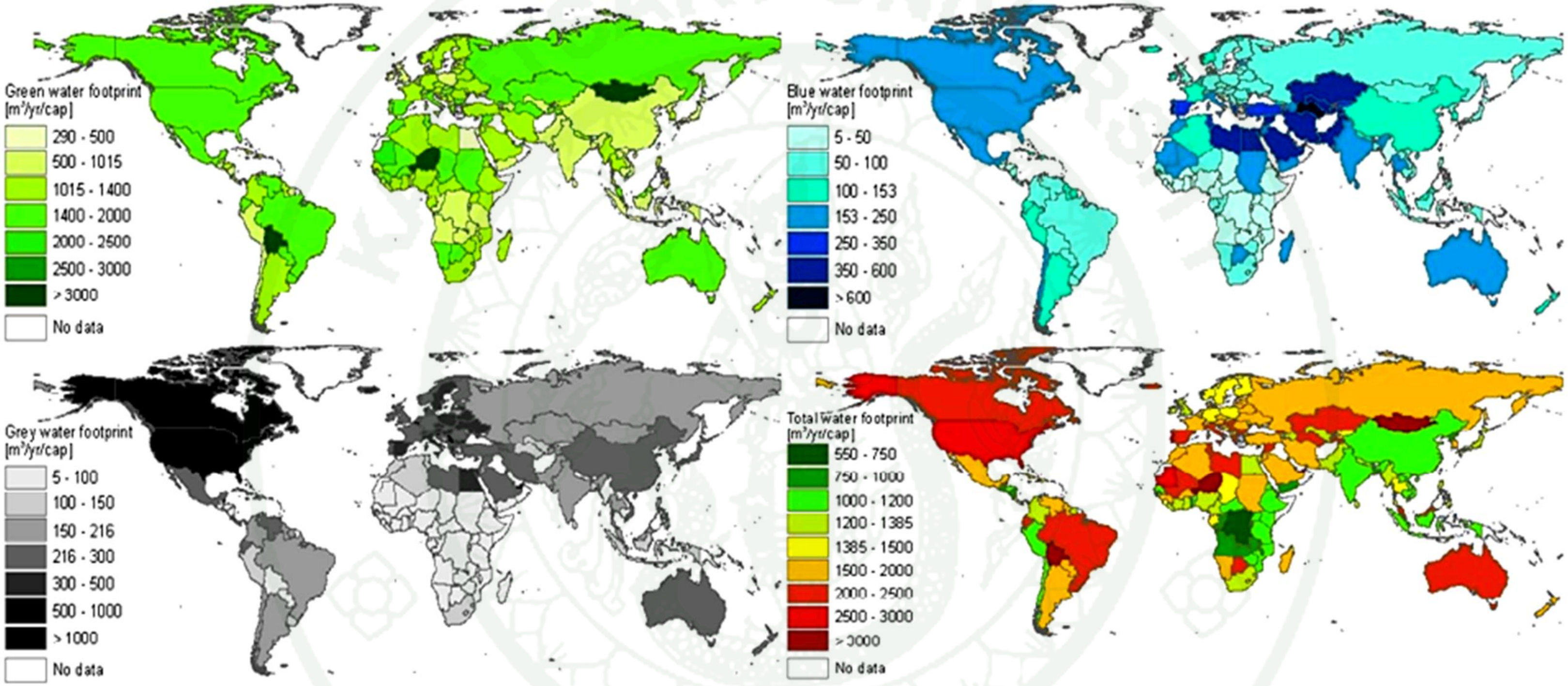

**Figure 5** The green, blue, grey and total water footprint of consumption per country in the period 1996ï 2005 ($m^3$/yr per capita) have been showed the total water footprint of consumption per country (bottomï right) in the map, countries shown in green have a water footprint that is smaller than the global average; countries shown in yellowï red have a water footprint larger than the global average.

**Source:** Mekonnen and Hoekstra (2011)

## 5. Water Availability

Water availability describes the availability of water for irrigation or consumption per capita per year in a region. Water availability was expressed in $m^3$ per year or $m^3$ per ton of product, based on the amount of rainfall on the agricultural surface used to produce products.

## 6. Water use

The water use is water withdrawal for different activities, and the water use of watersheds in Thailand is classified into five sections. The first section is domestic water and water needed for travel. The domestic water is estimated from population in each watershed. It is separated into urban and countryside because people in those areas need water in different amount. People in urban need water more than suburb. For example, people in urban need water use approximately 200 liter/capita/day, on the other hand people in suburb needs water use approximately 50 liter/capita/day. Moreover, data from Provincial Waterworks Authority is used to combine for estimation (HAII, 2013).

The second section is agriculture. It the major part of water use in each watershed in Thailand (Hoekstra, A.Y. and Mekonnen, M.M., 2012). The water use for agriculture is estimated by using mathematical model such as Water Uses Study Model (WUSMO), to calculate irrigation demand based on variety data; cultivated area, evapotranspiration, crop coefficient ($K_c$), species of crop, and cropping pattern. The other model is Soil and Water Assessment Tool (SWAT) which is used to assess water resource and impact of land management practices (Texas A and M university, 2009) by applying the overlap techniques of various parameters such as rainfall, land use, type of soil, etc.

Thirdly, water use estimation for industrial sector based on data from industrial registration of Department of Industrial Works in Thailand; products of each factory multiply with water use per unit of products.

The fourth is to estimate water use of livestock sectors by using types of livestock and amount of livestock based on Community Development Department. The method is applying amount of each animal multiple with water use rate per capita per day. For example, cattle consume water 80 liter/capita/day, pigs consume water 20 liter/capita/day and chickens consume water 3 liter/capita/day.

The final sector is water use for conservation of ecosystem. Water use in this sector can be calculated by water from head water which effect to water at downstream, so that it require water management system for balancing water system. Estimation of water use for downstream ecosystem conservation is assumed by minimum flow from water runoff statistic from January to April because this period is the lowest water flow (HAII, 2013)

## 7 Water Stress

Water covers threeï fourth of the earthôs surface, but fresh water contains only 2.5% of water on the earth. Moreover, twoï third of freshwater is maintained in ice and stored in groundwater. Hence, fresh water availability is limited and low when compare amount of global water. From the global have water limited and estimated that rate of the world population will increase to 9 billion people in 2050. Consequently, probability in water resource limited problem was relatively high.

Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes deterioration of fresh water resources in terms of quantity such as aquifer overïexploitation and dry rivers. (European Environment Agency [EEA], 2012)

### 7.1 Water stress index (WSI)

Water Stress evaluates damage to human health, to resources and to ecosystem quality. WSI represents the ratio of Water use to Water availability, with correction factors to take into account seasonal variations in water availability and normalized using a logistic function. WSI value ranges from < 0.1 to > 0.9. (Pfister *et al*., 2009)

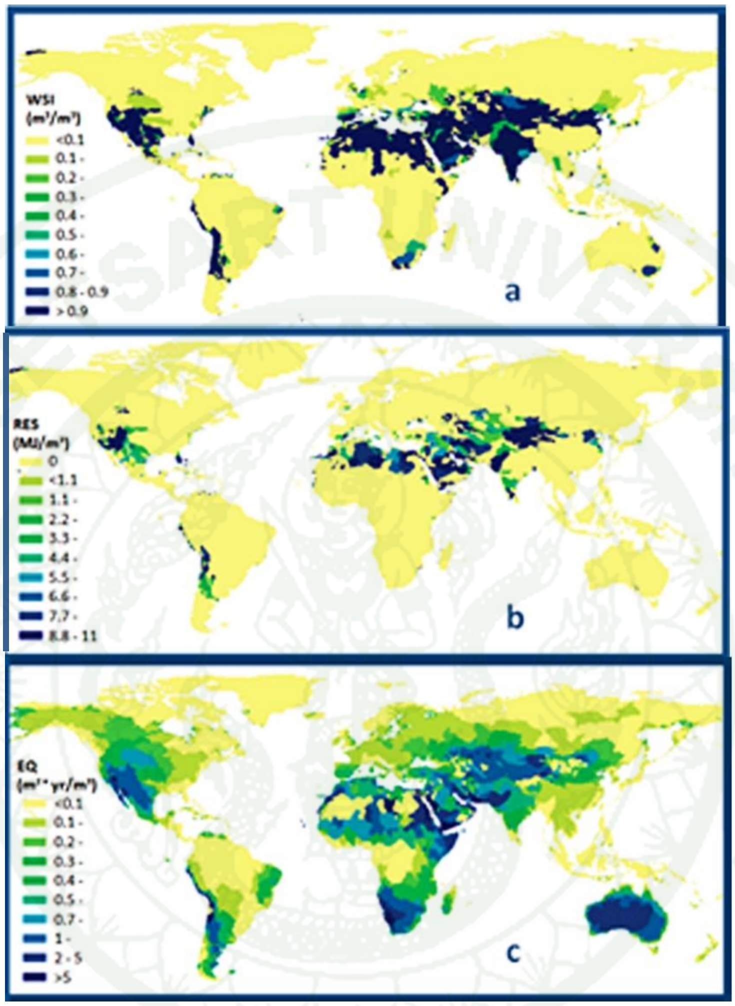

**Figure 6** Characterization and damage factors on the watershed level per m$^3$ water consumed: (a) Water stress index, (b) damage on resources, (c) damage on ecosystem quality.

**Source:** Pfister *et al.* (2009)

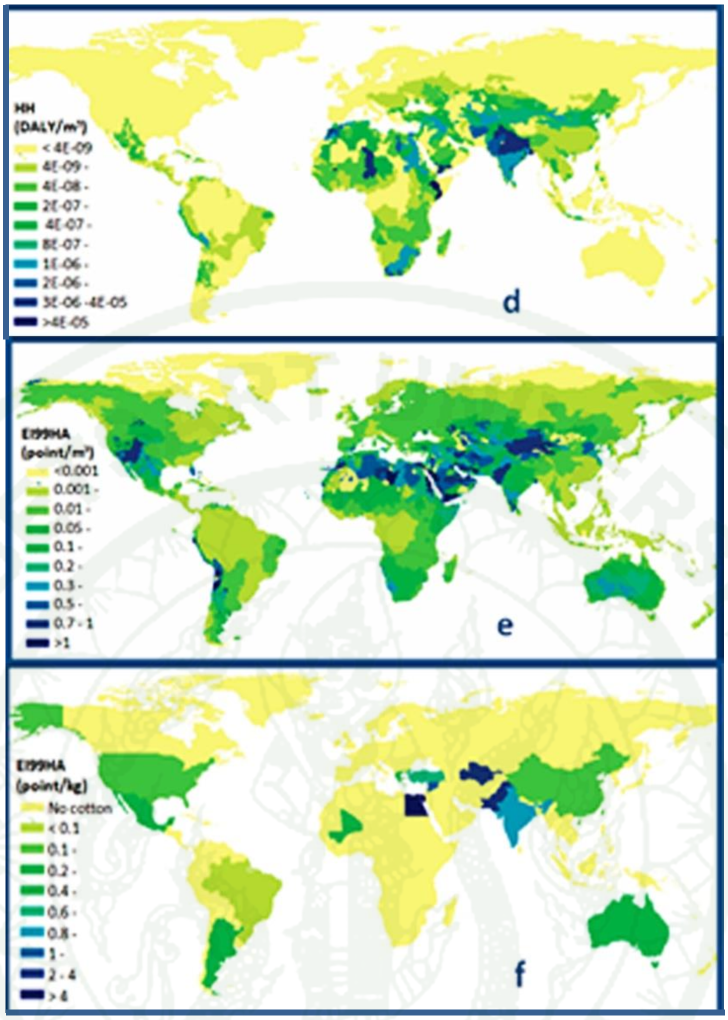

**Figure 7** Characterization and damage factors on the watershed level per $m^3$ water consumed: (d) damage on human health, and (e) aggregated Ecoï indicatorï 99 damage factor.Map (f) shows the aggregated Ecoï indicatorï 99 damage per kg cotton textile on the country level.

**Source:** Pfister *et al*. (2009)

## Literature review

Researchôs Gheewala *et al*. (2012) assesses the water footprint of ten staple crops grown of the 25 major watersheds in Thailand and evaluates the impact of crop water use in different regions/watersheds by the water stress index and the indication of water deprivation potential. The ten crops include major rice, second rice, maize, soybean, mungbean, peanut, cassava, sugarcane, pineapple and oil palm. The results show that there are high variations of crop water requirements grown in different regions results from difference of weather, and especially crop productivity. The results indicated that per hectare, the perennial trees like oil palm, pineapple and coconut have higher water footprint as compared to the field crops like rice, maize, cassava and sugarcane. For the field crops, cassava has the highest crop water requirement because its cropping period is over the whole year unlike rice which has a short cropping cycle. However, based on the current cropping systems, the Northeastern region has the highest water requirement for both green water footprint and blue water footprint. Rice (paddy) farming requires the highest amount of irrigation water, followed by the maize, sugarcane, oil palm and cassava. Major rice, sugarcane, second rice and cassava cultivation induce the highest water deprivation, respectively. The Mun, Chi and Chao Phraya watersheds that have high risk on water competition due to increase in production of the ten crops. The high risks come from the second rice cultivation. For biofuel crops, sugarcane cultivation is the major source of water stress in Mun, Chi and Tha chin whereas cassava causes high water stress in Mun, Chi and East Coast Gulf watersheds. Recommendations have been proposed for reducing crop water demand and for sustainable crops production in the future of Thailand. (Gheewala *et al*., 2012)

# MATERIALS AND METHODS

## Materials

### 1. Equipment and software

1.1 Computer Intel Core i5 and operating system Microsoft windows 7

1.2 CROPWAT8.0 model from FAO

## Methods

The inventory of inputs and outputs (water, energy, chemicals, etc.) for cassava starch production was based on primary data collection at four cassava starch factories located in the Mae Klong, Tha Chin, Mun and Bang Pakong basins in Kanchaburi, Ratchaburi, Nakhon Ratchasima and Chonburi provinces, respectively. The inventory of inputs and outputs (fertilizers, pesticides, energy, etc.) for cassava roots production was based on secondary data from Khongsiri (2009) and statistics from OAE (2012). Data on water availability such as rainfall, water runoff, water reserve and water on evapotranspiration of cassava (soil data, crop data) were collected from literature review and statistics from the Meteorological department, the Royal Irrigation Department, as well as CROPWAT 8.0 (FAO, 2010), as described in details below.

**Table 5** Location of factories is studied

| **Factory** | **F1** | **F2** | **F3** | **F4** |
|---|---|---|---|---|
| Province | Kanchanaburi | Ratchaburi | Chonburi | Korat |
| Basin | Tha Chin | Mae Klong | Bang Pakong | Mun |

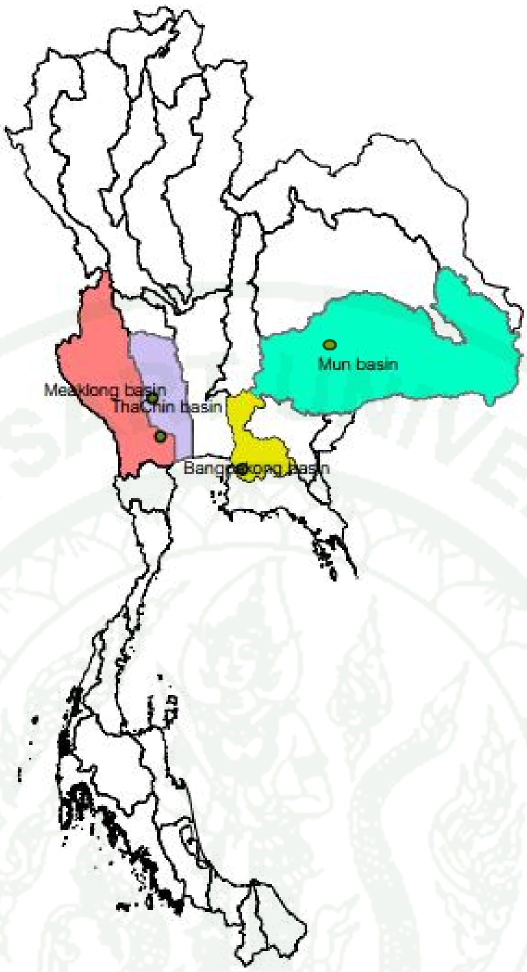

**Figure 8** Twentyï five basins in Thailand and position of site study

## 1. Life Cycle Inventory (LCI)

The inventory of inputs and outputs such as water, energy and chemicals for cassava starch production was based on primary data collection at four cassava starch factories located in the Mae Klong, Tha Chin, Mun and Bang Pakong basins in Kanchaburi, Ratchaburi, Nakhon Ratchasima and Chonburi provinces, respectively. The inventory of inputs and outputs (fertilizers, pesticides, energy, etc.) for cassava roots production was based on secondary data from literature review and statistics (OAE, 2012). Data on water availability such as rainfall, water runoff and water reserve including water on evapotranspiration of cassava (soil data, crop data) were collected from literature review and statistics from the Meteorological department, the Royal

Irrigation Department, as well as CROPWAT 8.0 (FAO, 2010) are described details below.

1.1 Life cycle inventory of cassava roots production

LCI of cassava roots production was collected as secondary data (Khongsiri , 2009; Keomary, 2010). Data collected included soil preparation, characteristic of cassava, practice of plantation, climate data, fertilizers, pesticides, energy and yield. The functional unit was the production of one ton of cassava roots.

The water usage to produce cassava roots was calculated using CROPWAT8.0 program.

1.2 Life Cycle Inventory (LCI) of cassava starch production

LCI of cassava starch production was collected for all the steps of the process, from the delivery of cassava roots to factories and including the following: roots preparation stage weigh fresh cassava roots apparent density from roots weight in air and in water to determine starch percentage. Soil and sand are removed as the roots through a cylindrical roots sieve and removed in roots washing process. Roots after sieving are transported into a water chamber to wash. Second, put roots cleaned in the chopper and raspers, rasping until they becomes fine particles and sediment them in the water. In this step, they appear as the slurry mix of starch, water, and fiber. Third, pumped fresh rasped roots slurry from raspers through a series of extractors. Starch slurry exiting the coarse extractor contains amount of fine fiber which must be removed in the fine extractor and fine extraction is repeated with a finer screen aperture. Fourth, separated starch slurry from fine extraction and dewatering in a horizontal centrifuge. Finally, drying Starch blown cake with hot air but this heatï moisture treatment can be problem to starch quality. In addition, wastewater from whole processing was brought to generate biogas. In small to middle starch plants typically use a cover lagoon system to reclaim biogas from anaerobic ponds while large plants use upï flow anaerobic sludge blanket (UASB). Some company use anaerobic fixedï film reactor because this system can reduced the construction area approximately oneï third and decreased odor surround the factory. The wastewater from whole process is treated and reused into some process again. All energy, water, wastewater, raw materials and waste in cassava starch production are calculated in reference to the functional unit of one ton of starch (at 13% moisture content wwb).

**Table 6** The data source of LCI

| Data | Data source | period |
|---|---|---|
| Rainfall | TMD | 1993ï 2012 |
| Wind speed | TMD | 1993ï 2012 |
| Humidity | TMD | 1993ï 2012 |
| Sunshine | TMD | 1993ï 2012 |
| Tempetature | TMD | 1993ï 2012 |
| Soil characteristics | DOA | 2012 |
| Crop characteristics | FAO | 2010 |
| Fertilizers | DOA | ï |
| Cultivated area and Crop yield | OAE | 2011ï 2012 |
| Water usage of cassava root production | Primary data[1] | ï |
| Water usage in cassava starch factories | Primary data | 2012 |
| Waste water in cassava starch factories | Primary data | 2012 |
| Raw materials in cassava starch factories | Primary data | 2012 |

[1] Calculated from CROW WAT8.0 program

## 2. Water Footprint calculation

The water footprint of cassava roots was calculated by the crop water footprint method (Hoekstra *et al*., 2011), using CROPWAT 8.0 model. The water footprints of crops depends on several factors such as climatic conditions, geographical location, soil characteristics, crop characteristics and agricultural practices (Marta *et al*., 2012).

**Table 7** Data requirement and sources of WF calculation

| **Data requirement** | **Data source** | **Period** |
|---|---|---|
| Climate Data | TMD | 1993ï 2012 |
| Soil characteristics | LDD | 2011 |
| Crop characteristics | FAO | 2010 |
| Cultivated area and Crop yield | OAE | 2011ï 2012 |
| Crop coefficient (Kc) | Kwanyuen, FAO | 2010 |

2.1 Calculation of crop water footprint

The calculation of the water footprint of cassava roots was based on the effective rainfall ($P_{eff}$) and evapotranspiration ($ET_c$) of cassava in the selected regions (Allen *et al.*, 1998). $ET_c$ was determined by the Penmanï Monteith equation adjusted by crop coefficient ($K_c$)

$$ET_c = ET \times K_c \qquad (1)$$

Where $ET_0$ is the reference evapotranspiration for cassava (mm/day) grown under optimal conditions, and $K_c$ is the crop coefficient to adjust the reference evapotranspiration to specific growth conditions. $K_c$ varies with the stage of growth (Table 8). The crop planting was in April and the length of the cropping season was set to 7 months with harvest in October, according to FAO (2010), although cropping is usually longer (9ï 10 months).

**Table 8** Comparison of crop coefficients ($K_c$) of cassava from different sources $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ are $K_c$ values for the beginning, middle and end of the growth cycle, respectively.

| **Source** | **$K_{c\ ini}$** | **$K_{c\ mid}$** | **$K_{c\ end}$** |
|---|---|---|---|
| $K_c$ specific to Thailand | 0.35 | 1.04 | 0.5 |
| $K_c$ average of FAO | 0.3 | 0.8 | 0.3 |

**Source**: Kwanyuen (2010); FAO (2010)

Green water was ($WF_{green}$) was calculated month by month as follows: If $ET_c > P_{eff}$, then $WF_{green} = P_{eff}$, and if $ET_c < P_{eff}$, then $WF_{green} = ET_c$. Blue water ($WF_{blue}$), was calculated month by month as follows: If $ET_c > P_{eff}$, then $WF_{blue} = ET_c$ï $P_{eff}$, and if $ET_c < P_{eff}$, then $WF_{blue} = 0$. Hence, blue water represents the irrigation needs calculated for the crop to grow under ideal conditions of water supply, but not necessarily the actual irrigation applied by the farmers. Indeed in the case of cassava cultivation in Thailand, irrigation is rarely applied because the additional income derived from increased yield is often not sufficient to cover the investment in irrigation infrastructures. This research calculate under optimal conditions and follow of all step below.

### 2.1.1 Estimated $ET_{green}$ and $ET_{blue}$.

$ET_{green}$ represents the volume of water evaporated by agricultural crops through evapotranspiration and $ET_{blue}$ is irrigation water needs when rainfall is not enough for the crop to grow under ideal conditions. Estimated $ET_{green}$ and $ET_{blue}$ under optimal conditions by using CROP WAT 8.0 model and. $ET_{green}$ is calculated summing of the minimum between rain effective and crop evapotranspiration of length of crop growing periods. $ET_{blue}$ is calculated from summing of crop evapotranspiration minus rain effective in length of growing period which can expanded in Equation 2, 3 respectively.

$$ET_{green} = \min (ET_c, P_{eff}) \text{ [length/time]} \quad (2)$$

$$ET_{blue} = \max (0, ET_c - P_{eff}) \text{ [length/time]} \quad (3)$$

### 2.2.2 Estimated the crop water usage (CWU, $m^3$/ha)

Estimated the green and blue components in crop water usage (CWU, $m^3$/ha) from Equation below, in which the factor 10 is meant to convert water depths in millimeters into water volumes per land surface in unit $m^3$/ha. The results is summation is of all period since first day of planting to the day of harvest (lgp stands for length of growing period in days).

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \quad \text{[volume/area]} \quad (4)$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \quad \text{[volume/area]} \quad (5)$$

### 2.2.3 $WF_{green}$ and $WF_{blue}$ Calculation

Calculation of the green and blue water footprint of growing a crop ($m^3$/ton). This is calculated as the crop water use (CWU, $m^3$/ha) divided by the crop yield (Y, ton/ha)

$$WF_{proc,green} = \frac{CWU_{green}}{Y} \quad \text{[volume/mass]} \quad (6)$$

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y} \quad \text{[volume/mass]} \quad (7)$$

2.2.4 The total water footprint of the process of growing crops ($WF_{proc}$) is the sum of green and blue water footprints.

$$WF_{proc} = WF_{green} + WF_{blue} \qquad (8)$$

$WF_{green}$ and $WF_{blue}$ were expressed per ton of cassava roots produced ($m^3$/ton roots), based on the average yield (Y) of cassava (ton/ha) in the different basins (Table 2), and as total amounts of water ($m^3$) required to produce enough roots to supply the starch factory year round (Kongboon and Sampattagul, 2012).

Grey water ($WF_{gray}$) was not considered in this study because the scenario of dilution of chemicals to acceptable levels is uncertain, in other words the calculated amounts of grey water are virtual and do not represent actual water usage. Moreover in the case of agricultural products, grey water calculations rely on considerable assumptions, with related uncertainties, regarding the diffusion of chemicals into the soil and water compartments.

### 2.2 Calculation of water usage of cassava starch factories

Water requirements in the cassava starch process was calculated as the total volume of water used in all steps of the process (Figure 1). Primary data on water use during the period 2012 was collected in four cassava starch factories in the Tha Chin, Mae Klong Mun and Bang Pakong basins, located in Kanchanaburi, Ratchaburi Nakhon Ratchasima and Chonburi province, respectively.

### 2.3 Calculation of Water Availability (WA)

Water availability (WA) in a given basin can be defined in two ways: (1) As the yearly rainfall in the basin, or (2) as the yearly water runoff from the basin. Hence in this study, both methods will be tested and results compared.

Firstly, water availability in the four basins of the study was calculated as the amount of rainfall, based on 20ï year monthly averages data for the period 1993ï

2012 (Meteorological Department). Secondly, water availability was calculated as the water runoff, follow the method in the literature review of Alcamo *et al*. (2003). The water runoff based on the average of years 2003 and 2009 (RID).

Moreover, this study separated two scenarios. The first, water availability is not into account the reservoirs. The second, water availability is into account the reservoirs based on available data from RID. Water availability was used as an indication of the fresh water available on land surfaces for agricultural, industrial and domestic uses. Water availability for starch production was expressed in m$^3$ per ton of starch, and was calculated as the amount of rainfall on the agricultural surface used to grow the roots necessary to produce 1 ton of starch. It is shown in Example 5 in Appendix B.

### 2.4 Calculation of Water Stress index (WSI)

Evaluation of water consumption in stress region of Thailand by using WSI is to evaluate the impact of water use for activities in the different regions and basins in Thailand according to Pfister *et al*. (2009).

WSI of basins calculated from the Equation 9 .WSI method developing by Pfister *et al*. in 2009 and Ridoutt and Pfister in 2010.

$$\mathrm{WSI} = \frac{1}{1 + e^{-6.4\mathrm{WTA}^{*}\left(\frac{1}{0.01}-1\right)}} \tag{9}$$

The value of water stress index as shown between 0.01 and 1.The level of water stress index are classified in Table 9

**Table 6** Water Stress Index Category

| **WSI** | **Category** |
|---|---|
| > 0.9 | Extreme |
| Ò0.9 | Severe |
| 0.5 | Stress |
| 0.1 ï <0.5 | Moderate |
| <0.1 | Low |

**Source:** Pfister *et al*. (2009)

The weighted water withdrawalï toï availability (WTA*) is the ratio of water withdrawal for agricultural, industry and household sector to hydrological and freshwater availability of each basin, adjusted with the variation factor (VF) to take into account seasonal variations of rainfall. In the study, WTA* is calculated from Equation 10 because the four watersheds are strongly regulated (SRF), due to water storage structures such as dams, which mitigates the seasonal rainfall variations.

$$\mathrm{WTA^{*}} = \sqrt{\mathrm{VF}} \times \mathrm{WTA} \quad \text{for SRF} \tag{10}$$

$$\mathrm{WTA^{*}} = \mathrm{VF} \times \mathrm{WTA} \, \text{for Nonï SRF} \tag{11}$$

VF was derived from the standard deviation of the precipitation distribution and defined as the aggregated measure of dispersion of the multiplicative standard deviation of monthly ($s^{*}_{\mathrm{month}}$) and annual precipitation ($s^{*}_{\mathrm{year}}$), assuming a logï normal distribution and considering precipitation data from 1993ï 2012 (TMD). The median variation factor of all watersheds is 1.8 (Pfister *et al*., 2009).

$$\mathrm{VF} = e^{\sqrt{\ln\left(s^{*}_{\mathrm{month}}\right)^{2} + \ln\left(s^{*}_{\mathrm{year}}\right)^{2}}} \tag{12}$$

WTA shown in Equation 13 is the ratio between total water withdrawals (water usage) divided hydrological availability of basin, and is calculated according to Equation 13

$$WTA_i = \sum_j WU_{ij}/WA_i \qquad (13)$$

Where $WTA_i$ is water withdrawal to water availability of each basin i ; $WU_{ij}$ refer to water withdrawal in basin i by user group j (three groups: industry, agriculture, and households).

$WU_{ij}$ can be calculated in two ways: (1) from total water need of all user group in each basin or (2) from the total water footprint of Thailand weighted either by the fraction of the population of Thailand living in the basin, or by the fraction of the surface area of Thailand comprised in the basin.

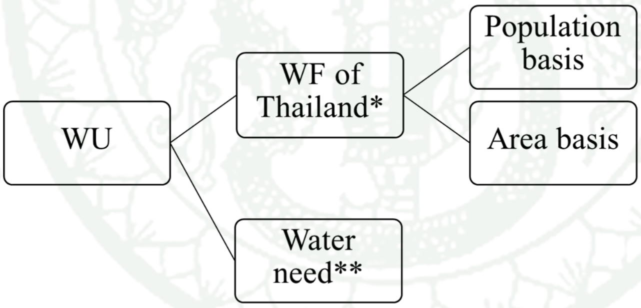

**Figure 9** The water usage calculation methods

$WA_i$ refer to hydrological availability in each basin i .The calculation of WAi is separated two method; first, the $WA_i$ calculated from combination of total precipitation of each basin i from 1993ï 2012 base on TMD and the stored water in reservoir at each basin from the end of year base on RID. (Gheewala *et al*., 2012). Second, from water availability ($WA_i$ ) as fast surface runoff plus groundwater recharge (Alcamo *et al*., 2003) . Hence, Water availability ($WA_i$ ) is calculated from the sum of total water runoff in each basin i and the stored water in reservoir at each basin from the end of year which shown i . So that the WSI calculation can be calculated in 12 method as following.

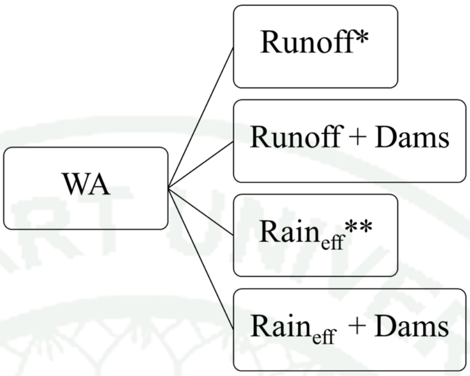

**Figure 10** The water availability calculation methods

Method 1'; WTA for basin i is calculated from the total water footprint of Thailand multiplied by area basis of basin i ($WF_{area\ i}$) divided by the sum of the water runoffs in basin i ($Runoff_i$) and water stored in reservoirs. It is represented in Equation 14.

$$WTA_i = WF_{area\ i} / (Runoff_i + Dams) \qquad (14)$$

Method 1; WTA for basin i is calculated from the total water footprint of Thailand multiplied by area basis of basin i ($WF_{area\ i}$) divided by the water runoffs in basin i ($Runoff_i$). It is represented in Equation 15.

$$WTA_i = WF_{area\ i} / (Runoff_i) \qquad (15)$$

Method 2'; WTA for basin i is calculated from the total water footprint of Thailand multiplied by area basis of basin i ($WF_{area\ i}$) divided combining of the effective rainfall in basin i ($Rain_{eff\ i}$) and reservoirs in basin i, is shown in Equation 16.

$$WTA_i = WF_{area\ i} / (Rain_{eff\ i} + Dams) \qquad (16)$$

Method 2; WTA for basin i is calculated from the total water footprint of Thailand multiplied by area basis of basin i ($WF_{area\ i}$) divided the effective rainfall in basin i ($Rain_{eff\ i}$), is shown in Equation 17.

$$WTA_i = WF_{area\ i} / (Rain_{eff\ i}) \qquad (17)$$

Method 3'; WTA for basin i is calculated from the total water footprint of Thailand multiplied by population proportionality of basin i ($WF_{pop\ i}$) divided by the sum of the water runoffs in basin i ($Runoff_i$) and water stored in reservoirs. It is represented in Equation 18

$$WTA_i = WF_{pop\ i} / (Runoff_i+Dams) \qquad (15)$$

Method 3; WTA for basin i is calculated from the total water footprint of Thailand multiplied by population proportionality of basin i ($WF_{pop\ i}$) divided by the water runoffs in basin i ($Runoff_i$). It is represented in Equation 18

$$WTA_i = WF_{pop\ i} / (Runoff_i) \qquad (19)$$

Method 4'; WTA for basin i is calculated from the total water footprint of Thailand multiply population proportionality of basin i ($WF_{pop\ i}$) divided combining of the effective rainfall in basin i ($Rain_{eff\ i}$) and reservoirs in basin i, is shown in Equation 20

$$WTA_i = WF_{pop\ i} / (Rain_{eff\ i}+ Dams) \qquad (20)$$

Method 4; WTA for basin i is calculated from the total water footprint of Thailand multiply population proportionality of basin i ($WF_{pop\ i}$) divided the effective rainfall in basin i ($Rain_{eff\ i}$), is shown in Equation 21

$$WTA_i = WF_{pop\ i} / (Rain_{eff\ i}) \qquad (21)$$

Method 5'; WTA for basin i is calculated from direct water withdrawals of basin i (Water needs$_i$) from industry, agriculture, and households which the data base on HAII divided combining of the water runoff in basin i (Runoff$_i$) and reservoirs in basin i, is shown in Equation 22

$$WTA_i = \text{Water needs}_i / (\text{Runoff}_i+\text{Dams}) \qquad (16)$$

Method 5; WTA for basin i is calculated from direct water withdrawals of basin i (Water needs$_i$) from industry, agriculture, and households which the data base on HAII divided the water runoff in basin i (Runoff$_i$), is shown in Equation 23

$$WTA_i = \text{Water needs}_i / (\text{Runoff}_i) \qquad (23)$$

Method 6'; WTA for basin i is calculated from direct water withdrawals of basin i (Water needs$_i$) from industry, agriculture, and households, by HAII divided combining of the effective rainfall in basin i (Rain$_{eff\ i}$) and reservoirs in basin i, is shown in Equation 24

$$WTA_i = \text{Water needs}_i / (\text{Rain}_{eff\ i} +\text{Dams}) \qquad (17)$$

Method 6; WTA for basin i is calculated from direct water withdrawals of basin i (Water needs$_i$) from industry, agriculture, and households, by HAII divided the effective rainfall in basin i (Rain$_{eff\ i}$), is shown in Equation 25

$$WTA_i = \text{Water needs}_i / (\text{Rain}_{eff\ i}) \qquad (18)$$

# RESULTS AND DISCUSSION

This research studies different areas in Thailand namely Kanchanaburi, Ratchaburi, Nakhon Ratchasima and Chonburi provinces residing in Tha Chin, Mae Klong, Mun and Bang Pakong basins, respectively. Those mentioned provinces have a high cassava planted area in range 10,950ï 281,520 ha (Office of Agricultural Economics, 2013). The study shows water usage for cassava cultivation, cassava starch production in factories of those basins and the WSI in those basins.

## 1. Life Cycle Inventory (LCI)

The inventory analysis in this study was described into two parts, life cycle inventory of cassava roots production and life Cycle Inventory of cassava starch production.

The inventory of inputs and outputs such as water, energy and chemicals for cassava starch production was based on primary data collection at four cassava starch factories located in the Mae Klong, Tha Chin, Mun and Bang Pakong basins in Kanchaburi, Ratchaburi, Nakhon Ratchasima and Chonburi provinces, respectively. As shown in Table 10. The inventory of inputs and outputs (fertilizers, pesticides, energy, etc.) for cassava roots production was based on secondary data from literature review and statistics (Keomary, 2010; OAE, 2012) as shown in Appendix Table C1. Data on water availability such as rainfall, water runoff and water reserve including water on evapotranspiration of cassava (soil data, crop data) were collected from literature review and statistics from the Meteorological department, the Royal Irrigation Department, as well as CROPWAT 8.0 program (FAO, 2010) are described details below.

### 1.1 Life cycle inventory of cassava roots production

LCI of cassava roots production is a secondary data which collection and inventory consists of soil preparation, characteristic of cassava, practice of planted, climate data, fertilizers, pesticides, energy and yield which relative and used in cassavas production in unit one ton of cassava roots is shown in Appendix Table C1 by Khongsiri (2009) and Keomary (2010).

In this report we focus on water to plant cassava roots which calculated by CROPWAT8.0 program because the water usage to plant cassava root from CROPWAT8.0 program more than the practice of agriculturists.

### 1.2 Life Cycle Inventory (LCI) of cassava starch production

LCI of cassava starch production was collected for all the steps of the cassava starch production, from root washing to Bagging. All energy, water, wastewater, raw materials and waste in cassava starch production are calculated in reference to the functional unit of 1 ton of starch (at 13% moisture content wwb) as shown in Table 10.

**Table 10** Life cycle inventory of cassava starch production

| Input | | | Output | | |
|---|---|---|---|---|---|
| **type** | **quantities** | **unit** | **type** | **quantities** | **unit** |
| **material** | | | **product** | | |
| Cassava root | 4.125±0.372 | ton | Cassava starch | 1 | ton |
| water | 23.868±9.454 | $m^3$ | Cassava peel(wet) | 0.133±0.116 | ton |
| **fuel/electricity** | | | Cassava pulp | 1.660±0.668 | ton |
| diesel | 3.277±5.036 | liter | **Water pollution** | | |
| biogas | 170.264±66.402 | $m^3$ | COD | 47.50±33.748 | kg |
| electricity | 229.618±69.696 | kWh | | | |
| Heavy fuel oil | 0.063±0.108 | liter | | | |

## 2. Water usage and COD value of factories in watersheds

The data of studied factories are shown in Table 11. The results showed that factory in Mae Klong basin exhibits the highest amount of water used from farming which calculated from the crop evapotranspiration; it is resulted from the combination of area of cassava produced and the evapotranspiration of cassava fields; the value of temperature, solar radiation, wind speed, humidity and duration time of crop plant have effect to crop evapotranspiration (FAO, 2014). In particular, the temperature and solar radiation are main effect to the evapotranspiration because it able to change large quantities of liquid water in water vapor. Moreover, the value of native starch production have effect when we calculated in unit per ton of native starch. Water used by cassava factories in each basin is directly collected; water supplied in cassava factories are from irrigation water, water runoff and ground water. Factory 4 (F4) in the Mun basin consumes the highest amount of water usage, whereas that in The Bang Pakong basin consumes the lowest amount of water usage. It is caused from the different type machineries used and water management practices in each factories. In addition, the factory in Bang Pakong basin consumes the lowest amount of water usage because the factory has the highly effective waste water recycle system that results in decreasing of influent.

Influent of the factory in Mun basin lower than effluent for biogas production that results from the influent of production process not into account water from cassava root and ground water. The amount of waste water used for biogas production lower than influent of factory because all of the effluent after cassava starch process is divided into two parts. The main part has high organic matter was sent to biogas production and the other part was directly sent to open lagoon for coarse treatment. Wastewater treatment by lagoons is effective enough for effluent from cassava root washing process because it contains low organic matter.

The quantity of water usage for produced cassava starch represented in total water requirements for factory activity (Table 11). The water used for farming is the main factor affecting to the highest amount of total water requirements of factory activity which consumed water in Mae Klong basin. The quantity of influent and effluent for biogas production of factory 3 (F3) in Bang Pakong basin has the lowest is mean this factory has effective waste water recycle system and it result in the amount of waste water has a lot of COD after pass biogas production.

Usually amount of COD after biogas production rapidly decreased because of anaerobic digestion, but the ratio of COD between before and after biogas production of Factory 1 (F1) in Tha Chin basin lower than the others. It indicates that the factory has effective biogas production because the processes extremely decrease organic matter so amount of COD decrease.

Production capacity of the starch factories in Mun basin has the highest on account of the capacity and ability to produce of factory.

**Table 11** Water usage and COD value of factories in watersheds

| | **Units** | **F1** | **F2** | **F3** | **F4** |
|---|---|---|---|---|---|
| Basin | | Tha Chin | Mae Klong | Bang Pakong | Mun |
| Production capacity of the starch factory | tons starch/year | 29,480 | 36,899 | 68,180 | 71,000 |
| Water used for farming (evapotranspiration)[1] | $m^3$/ton of starch | 1,066.46 | 1,372.77 | 975.03 | 799.46 |
| Water used by factory | $m^3$/ ton of starch | 33.25 | 25.00 | 13.25 | 36.00 |
| Total water requirements for factory activity | $m^3$/ ton of starch | 1,099.70 | 1,397.77 | 988.29 | 835.46 |
| Wastewater used for biogas production | $m^3$/ ton of starch | 21.22 | 23.49 | 6.83 | 37.00 |
| COD of wastewater used for biogas production | mg/liter | 21,326 | 18,692 | 27,081 | 18,579 |
| Wastewater after biogas production | $m^3$/ ton of starch | 20.46 | 16.99 | 6.83 | 37.00 |
| COD of wastewater after biogas production | mg/liter | 362 | 1,148 | 3,272 | 2,632 |

[1] assume that the amount of cassava yield per area is the same for all four areas are the water footprint of the starch factories.

## 2. Water footprint of cassava starch in relation to water availability

Calculation of the green and blue water footprint of cassava is calculated as the crop water use (CWU) to the crop yield (Y). The green water footprint and blue water footprint of cassava root production in the four basins of the study was calculated using two different sets of $K_c$. The former is the FAO, and the letter is specifically studied in Thailand (Kwanyuen *et al*., 2010) (Table 8). The two sets of $K_c$ gave different absolute values of WF, but the ranking is similar among the four basins that F2 in the Mae Klong basin (Ratchaburi) shows the highest green water footprint and blue water footprint, followed by F3 in Bang Pakong basin (Chonburi), F1 in Tha Chin basin (Kanchanaburi) and the F4 in Mun basin (Nakhon Ratchasima). The lower $WF_{green}$ of cassava roots in Nakhon Ratchasima is explained by differences in meteorological condition: rainfall, temperature, solar radiation, wind speed, humidity and duration time of crop plant. Resulting in the lowest evapotranspiration in Nakhon Ratchasima. Cassava yield was considered as a possible explanation; however, yields were similar in the four basins (Table 2). The range of cassava water footprint in four studied basins has value closely to the range of cassava water footprint of Thailand with approximately 394ï 413 $m^3$/ton of cassava root (Gheewala *et al*., 2014). The value of cassava water footprint in this research has lower range than that in Thailand. The possible explanation could be smaller calculating period referred from cassava cultivation time covering Aprilï October or 7 months, whereas value of cassava footprint done by other research was calculated for all year round.

The water footprint of cassava starch production was calculated for the root cultivation and the cassava processing steps (Table 12). For root cultivation, the four factories in each basins were ranked in the same way as with WF calculations; with the Mun basin shows the lowest water usage. An additional factor to explain this result is the higher starch content of the roots in F4 at Nakhon Ratchasima, which means that less roots and less agricultural surface are needed to produce one ton of starch. In contrast, the starch factory 4 in the Mun basin used the most water with was 36$m^3$/ton starch, which may reflect differences in the type of machinery used and/or differences in water management practices between factories.

**Table 7** Water footprint of cassava root in Thailand

| **Factories** | **WF using $K_{c\ \mathrm{Thailand}}$ ($m^3$/ton roots)** | | | **WF using $K_{c\ \mathrm{FAO}}$ ($m^3$/ton roots)** | | |
|---|---|---|---|---|---|---|
| | **Green** | **Blue** | **Total** | **Green** | **Blue** | **Total** |
| F1 | 242 | 3.5 | 246 | 186 | 0 | 186 |
| F2 | 285 | 21 | 306 | 226 | 5 | 231 |
| F3 | 266 | 0.6 | 266.8 | 201 | 0 | 201 |
| F4 | 199 | 0.2 | 199.2 | 151 | 0 | 151 |

The water availability was markedly low in the Mun basin (F4) due to low rainfall in Nakhon Ratchasima province. As a consequence, the ratio of water usage to water availability was comparable in the four basins (44ï 54%) even though overall water usage for cassava starch production was lower in Nakhon Ratchasima province. In terms of water scarcity, a ratio of water usage to water availability above 40% corresponds to severe water stress (Pfister *et al.*, 2009). In other terms, cassava cultivation and cassava starch production of factories in the four basins of the study do not contribute to water depletion since most water use is from evaporation of rainfall, and they also do contribute significantly to the replenishment of water resources.

**Table 8** Water usage for cassava starch production and Water availability

| **Factories** | **Water usage for cassava cultivation ($m^3$/ton starch)** | **Water usage for cassava starch factory ($m^3$/ton starch)** | **Water availability ($m^3$/ton starch)[1]** | **Ratio of Water usage / Water availability (%)** |
|---|---|---|---|---|
| F1 | 1061 | 33.25 | 2461.75 | 44.45 |
| F2 | 1372 | 25 | 2596.97 | 53.82 |
| F3 | 975 | 13.25 | 2162.33 | 45.70 |
| F4 | 799 | 36 | 1782.44 | 46.85 |

[1] Water availability was calculated as the amount of rainfall on the surface used to grow the roots necessary to obtain 1 ton of cassava starch.

## 3. Water Stress Index (WSI) in the four basins

To study impact of water use by cassava starch production in the different basins is not sufficient, so that we apply WSI as a tool to the assessment of the water scarcity in those four basins in Thailand. Usually, WSI is calculated from the concept of ratio of water used to water availability by Pfister *et al*. (2009). The interpretation of water availability was distinguished into 12 equations as shown in Equation 14ï 25. The source of water use and water availability is assessed from different resources. In order to assess the sensitivity of the method to the source of data, we used the following data. The first, water use from WF of Thailand (Hoekstra and Mekonnen, 2012) adjusted proportionally to (i) the surface of the basin ($\mathrm{WF}_{\mathrm{area}}$) and (ii) the population of the basin ($\mathrm{WF}_{\mathrm{pop}}$).

The second, water use from Hydro and Agro Information Institute (HAII) is classified into five sections as the domestic water and the water need for tourism, the water use for agriculture, water use for industry, water use of livestock and water use for conservation of ecosystem. (HAII, 2013).

The third, the water availability is estimated from the water runoff based on RID in 2003 and 2009**.**

The fourth**,** the water availability is estimated from the average annual rainfall data from from 1993ï 2012 base on TMD which in agricultural sector, the rainfall is considered in terms of the amount of rainfall used by plants named as effective rainfall ($\mathrm{Rain}_{\mathrm{eff}}$).This research assumed that $\mathrm{Rain}_{\mathrm{eff}}$ for all basins in Thailand was logï normally distributed (McMahon *et al*., 2007), although tests with the 25 basins of Thailand indicated that respectively 60% and 40% of basins better fit the normal distribution and logï normal distribution. This result may be based by the fact during the 4ï 5 months of dry season Thailand, precipitations are zero-mm, which we were forced to ignore in order to logï transform the data.

To calculate WSI, we followed Pfister *et al*. in 2009. The VF is calculated by using rainfall data in different watersheds based on 20ï year monthly averages data covering 1993ï 2012 (TMD) and water in reservoirs of those watersheds. This research uses different methods to calculate the VF values. In order to assess the sensitivity of the method to VF, we tested the calculations of VF by using three following methods:

Method 1, transform the rainfall data X into ln(X), then calculate the monthly and yearly averages ($m_{month}$, $m_{year}$) and standard deviations ($s^*_{month}$ and $s^*_{year}$) of the transformed data

Method 2, calculate the monthly average ($m_{month}$), yearly averages ($m_{year}$) and standard deviations ($s_{month}$, $s_{year}$) of the rainfall in the original data X, then use the equation (2); $CV=\square\exp\square\square^{\square}\square- 1\square^{\square\square}$ proposed by Limpert *et al*. (2001) to calculate s*month and s*year directly. It is presented in Example 7 in Appendix B.

Method 3, calculate the monthly and yearly averages of the original rainfall data, then transform the averages X into ln(X). Finally calculate $s^*_{month}$ and $s^*_{year}$ using the transformed data.

The calculated VF values shown in Table 14 are higher than the global average VF value of 1.8 and the VF obtained from other research which primarily studied in Thailand as discrepancy of data. Hence, this study used VF value from method 3 to represent WSI calculation of each basin.

**Table 9** Variation factor value of watersheds

| VF Methods | Kan | Rat | Korat | Chon |
|---|---|---|---|---|
| VFï method 1 | 5.83 | 6.64 | 5.12 | 6.11 |
| VFï SRFï method 1 | 2.41 | 2.58 | 2.26 | 2.47 |
| VFï method2 | 1.29 | 1.33 | 1.28 | 1.28 |
| VFï SRFï method2 | 1.14 | 1.15 | 1.13 | 1.13 |
| VFï method3 | 4.12 | 4.74 | 4.42 | 3.48 |
| VFï SRFï method3 | 2.03 | 2.18 | 2.10 | 1.86 |

**Table 10** Present the WTA calculated with the different sources of data:

| Methods | **Kan** | **Rat** | **Korat** | **Chon** |
|---|---|---|---|---|
| M1 | 2.67 | 0.45 | 1.30 | 0.70 |
| M1' | 2.32 | 1.42 | 1.30 | 0.92 |
| M2 | 0.31 | 0.30 | 0.30 | 0.27 |
| M2' | 0.30 | 0.17 | 0.29 | 0.26 |
| M3 | 3.82 | 0.21 | 1.50 | 1.31 |
| M3' | 3.32 | 0.09 | 1.24 | 1.15 |
| M4 | 0.44 | 0.14 | 0.35 | 0.51 |
| M4' | 0.43 | 0.08 | 0.33 | 0.49 |
| M5 | 6.10 | 0.53 | 0.97 | 1.02 |
| M5' | 5.31 | 0.24 | 0.81 | 0.89 |
| M6 | 0.70 | 0.36 | 0.23 | 0.40 |
| M6' | 0.69 | 0.20 | 0.22 | 0.38 |
| WTA published by Shabbir | 0.23 | 0.03 | 0.39 | 0.06 |

As all river basins in Thailand have dams and can be considered as strongly regulated flows. Consequently, we used $VF_{SRF}$ equal to $\sqrt{VF}$ for calculation the WTA* and WSI, as follows: WTA* = WTA × $VF_{SRF}$. WSI was calculated according to Equation 9 below by Pfister *et al*. (2009). It is shown below.

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

Methods to assess the impacts of water use in LCA are under development and testing by different research teams around the world. In order to contribute to a consistent methodology, this research tested different ways of calculating WSI. Our results in Table 16 indicate that WSI is sensitive to the following factors:

WTA values vary depending on source of data. Then it is necessary to check and justify the reliability of data, and if possible to get different datasets from different sources for crossï checking and sensitivity analysis.

**Table 16** Present the WSI calculated with the different sources of data by using VF method 3

| Methods | Kan | Rat | Korat | Chon |
|---|---|---|---|---|
| WSI published by Shabbir | 0.287 | 0.018 | 0.927 | 0.026 |
| WSI by Pfister: 0.534 for the whole Thailand | 0.481 | 0.014 | 0.020 | 0.592 |
| M1 | 1.000 | 0.838 | 1.000 | 0.977 |
| M1' | 1.000 | 0.146 | 1.000 | 0.937 |
| M2 | 0.356 | 0.408 | 0.376 | 0.209 |
| M2' | 0.340 | 0.094 | 0.334 | 0.182 |
| M3 | 1.000 | 0.149 | 1.000 | 1.000 |
| M3' | 1.000 | 0.036 | 1.000 | 1.000 |
| M4 | 0.756 | 0.065 | 0.527 | 0.822 |
| M4' | 0.738 | 0.028 | 0.474 | 0.769 |
| M5 | 1.000 | 0.940 | 1.000 | 0.999 |
| M5' | 1.000 | 0.220 | 0.998 | 0.998 |
| M6 | 0.990 | 0.592 | 0.176 | 0.540 |
| M6' | 0.988 | 0.135 | 0.157 | 0.476 |

VF values vary depending on the method of calculation for the comparison of our 3 methods and the method of Gheewala *et al.*, 2014. The suitable method for calculating VF was proposed to be Method 3 because it is applicable for most climates, including climates with a marked dry season (except very dry climates when zero-mm rainfall really is zero-mm over many years), and reflects the variability in rainfall between seasons better than the method 2 (Limpert equation); Limpert gives lower s* and lower VF, which doesnôt make sense in a contrasted climate such as Thailand with 4ï 5 months with nearly no rains, and 4ï 5 months with heavy rains. Consequently WSI vary (a lot). In order to compare publications, it is therefore important to describe in details which approach was used to calculate WTA and VF. We suggest the following calculation steps:

(1) Calculate WTA using the most reliable data available. To do an independent estimation of water use (as proposed by Gheewala *et al*., 2014) based on more reliable/upï toï date national statistics of agricultural and industrial activities and rural and urban populations might be a better option than using sparser statistics of water use.

(2) Calculate VF using the method 3 (ñmonthly averages followed by logï transformò). This method gives VF higher than the global median VF (=1.8), which reflects appropriately the contrasted rainfall patterns in Thailand, with marked rainy and dry seasons. Another advantage is that the months with zero-mm rainfall are taken into account. In contrast, the method 2 (Limpert *et al*., 2001) underestimates VF values, with values lower than the global median VF.

**Table 17** Summary of suit calculation to calculate WSI and reasons to use.

| Methods | Usable | Reasons | Source |
|---|---|---|---|
| Water use | Yes | The different methods to estimate water use have suitable justifications | HAII, Hoekstra (2004) |
| Water availability as Runoff | Not recommended | Data incomplete / unreliable leading to high WTA | RID (2003,2009) |
| Water availability as Rain$_{eff}$ | Yes | Most reliable source of data | TMD |
| Dam | Yes | Represents several years of accumulated rainfall | RID |
| VF method 1 | Not recommended | Ignores months with 0mm rainfall | Pfister *et al*. (2009) |

**Table 17** (Continued)

| Methods | Usable | Reasons | Source |
|---|---|---|---|
| VF method 1 | Not recommended | VF equation needs to be modified if we assume normal distribution of rainfall (equation is related to multiplicative standard deviation of logï normal distributions, not applicable to standard deviations of original data) | Gheewala *et al*. (2014) |
| VF method 2 | Yes | Valid method of estimation of multiplicative standard deviation based on m and s of the original data | Limpert *et al*. (2001) |
| VF method 3 | Yes | Monthly averages are also logï normal distributed, and avoid the problem of 0mm rainfall data to logï transform | Our method |

The results from Table 16 show that the M1, M2 and M3 are suitable because runoff is too low and WSI is too high. Except Ratchaburi in Mae Klong basin is not discriminant between the 3 basins; Thachin, Bang Pakong, Mun. Moreover there overestimate the water stress in Thailand. The different between $WTA_{area}$ and $WTA_{pop}$ is shown in Table 15; the $WTA_{area}$ gives more weights agricultural activities, and $WTA_{pop}$ gives more weight to population density in the four basins. Overall WSI values are fairly high, except Ratchaburi in Mae Klong basin (with method M4', WSI values are higher than 0.4, which is the threshold for severe water stress according to Pfister *et al*., 2009). This indicates a significant pressure of human activities on water resources in three of the four basins investigated.

When compared WSI in this research with WSI of Thailand by Pfister *et al.* (2009), it explained that our methods M4 or M4' give the closest WSI value to WSI of Pfister *et al.* (2009), except the Mun basin on the Isan plateau (northeastern Thailand). This is because we considered the actual water availability in the Mun basin, whereas Pfister *et al*. used a dataset where the Mun basin is aggregated with the Mekong basin resulting in a much higher water availability. We may also conclude that Pfisterôs source of data for water use gave more weight to population than to agricultural areas.

The other comparison with Gheewala *et al*. (2014) presented our WSI values are different with WSI in Thailand by Gheewala *et al*. (2014) because our WSI have different calculation methods for VF (calculated from the equation; X/AVERAGE $(X)^2$), and different sources of data for WTA (both water use and water availability). Our WSI were higher overall, except Mun basin, so conclusions about the state of water stress in Thailand may need further investigations.

There is high variation between methods of calculations of WSI. This indicates data obtained from different sources shows the same trend, but not exact figures when compared with other research. In addition, different types of water used in calculation namely runoff or effective rainfall ($Rain_{eff}$) also presents different WSI values. It makes the WSI method difficult to interpret and to compare with different studies. Therefore, publications should provide a selfï assessment of the reliability of the data used in the scale of 1 to 10 as well as the reasons for the variations in the data (see Table 18). Where; 10 is good quality data, 5 is average quality data and 1 is poor quality data. This approach is based on the recommendations for data quality requirements in the LCA standard guidelines ISO 14040–14044.

**Table 18** The qualitative assessment of the data sources

| **Data** | **Reliability (1–10)** | **Reasons** |
|---|---|---|
| Rain fall | 8 | Stable protocol for data collection; wellï established international standard method used for more than 30ï 40 year |
| Evapotranspiration | 7 | Relies on climate model which may be not close to reality (wellï established method developed by FAO and used worldwide) |
| Water runoff | 5 | Missing data (at least in Thailand) |
| Density of population | 4 | Several assumptions on the water needed for the different activities |
| Types of human activities | 4 | Several assumptions on the water needed for the different activities |

In current, the Thailand government (ministry of agriculture and cooperative) has policies to support cultivation of crop for alternative fuels such as cassava, oil palm and sugar cane. These consume a lot of resources especially the water which is a limited resource. Therefore suitable the water management and zoning for cultivation in Thailand is necessary. This research can contribute to the database to analyze the water management in each basin in Thailand .moreover is helpful to define zoning cultivation in some part of Thailand (ministry of agriculture and cooperative, 2014).

# CONCLUSIONS AND RECOMMENDATION

The water usage of cassava starch production was assessed in four river basins in Thailand: Mae Klong (Ratchaburi province), Tha Chin (Kanchanaburi province), Mun (Nakhon Ratchasima province) and Bang Pakong (Chonburi province). Cultivation of cassava roots used most water, 95ï98% of total water use for starch production through evapotranspiration of rainwater, without additional irrigation. In contrast, the processing stage used surface water or groundwater, which have impact for the river basin, then since the water for the factory withdrew from local water resources (canal, river, or groundwater). In one case, the factory manages its yearly supply of freshwater by storing surface water in lagoons during the yearly floods at the end of the rain season. This strategy can be considered as having no impact on water scarcity, because the water withdrawn from the basin for storage would otherwise flow to the sea within a short time scale.

The total water footprint of cassava root production shows 199ï306 $m^3$/t root, and total water footprint for cassava starch production ranged from 835ï1397 $m^3$/t starch, with cassava processing using 13.25ï36 $m^3$/t starch. Differences of WF between basins could be explained by climatic conditions (temperature, solar radiation, wind speed, humidity and duration time of crop plant [FAO, 2014]), soil characteristics, and starch content of the roots. A way to reduce total water usage would be to increase the yields and/or the starch content of the roots, which would reduce the surface of agricultural land required to produce 1 ton of starch. The water usage for cassava starch production corresponded to 44ï54% of the water availability (rainfall) in the river basins, which can be considered as high according to Pfister *et al*. (2009).

The results indicated the sensitivity of WSI to various factors as variation factor (VF), source of data (such as HAII, RID). The suitable method for calculating VF was proposed to be Method 3 because it is applicable to both dry season and rainy season. It could solve the problem of the zero-mm rainfall data in the dry season. In addition, Method 3 gave the values of s* and VF that were more suitable to the climate of Thailand. Moreover, the VF values obtained were higher than the global average value

(1.8), reflecting the high variations in rainfall between the dry and wet seasons in Thailand

The WSI value are higher than 0.4 and higher than others research (e.g. the primary research in Thailand by Gheewala *et al*., 2014), except Ratchaburi in Mae Klong basin. It is the threshold for severe water stress according to Pfister *et al*. (2009).

# LITERATURE CITED

Alcamo *et al*. 2003. Development and testing of the WaterGAP 2 global model of water use and availability. **Hydrological Sciences.** 48(3): 317ï 337

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998. **Crop Evapotranspiration–Guidelines for Computing Crop Water Requirements: FAO Irrigation and Drainage Paper No. 56**. Food and Agriculture Organization, Rome.

Berger, M., R. van der Ent, S. Eisner, V. Bach and M. Finkbeiner. 2014. Water Accounting and Vulnerability Evaluation (WAVE): Considering Atmospheric Evaporation Recycling and the Risk of Freshwater Depletion in Water Footprinting. **Environ. Sci. Technol.** 48(8): 4521ï 4528.

Chavalparit, O. and M. Ongwandee. 2009. Clean technology for the tapioca starch industry in Thailand. **Journal of Cleaner Production** 17: 105ï 110.

Department of Agriculture (DOA). 2010. **Cassava**. Available Source: http://it.doa.go.th/vichakan/news.php?newsid=14, February 20, 2013.

DOA. 2012. **Cassava varieties conclusion of the Department of Agriculture for industry**. (in Thai) Available Source: www.doa.go.th/fcri/images/files/var.pdf, September 15, 2013.

European Environment Agency (EEA). 2012. **Water stress**. Available Source: www.eea.europa.eu/publications/92ï 9157ï 202ï 0/3.5.pdf, September 9, 2013.

Environmental Protection Agency. 1993. **Life Cycle Assessment: Inventory Guidelines and Principles**, Ohio.

Food and Agriculrure Organization of the United Nations (FAO). 2010. **CROPWAT 8.0 model**. Retrieved from Food and Agriculture Organization of The United Nations. Available Source: http://www.fao.org/nr/water/infores_databases _cropwat.html., September 9, 2013.

FAO. 2013. **Save and grow: cassava a guide to sustainable production intensification**. Available Source: http://www.fao.org/ag/saveï andï grow/cassava/index_en.html.

Gheewala, S.H., T. Silalertruksa, P. Nilsalab, R. Mungkung, S.R. Perret and N. Chaiyawannakarn. 2014. Water Footprint and Impact of Water Consumption for Food, Feed, Fuel Crops Production in Thailand. **Water** 6: 1698ï 1718.

Hoekstra, A.Y. and A.K. Chapagain. 2007. Water footprints of nations: water use by people as a function of their consumption pattern. **Water Resour. Manage.** 21: 35ï 48.

Hoekstra, A.Y., A.K. Chapagain, M.M. Aldaya and M.M. Mekonnen. 2011. **The Water Footprint Assessment Manual: Setting the global standard**. Available Source:http://www.waterfootprint.org/?page=files/ WaterFootprintAssessmentManual, February 20, 2013.

Hoekstra, A.Y. and M.M. Mekonnen. 2012. The Water Footprint of Humanity. **Proceedings of the National Academy of Sciences** 109 (9): 3232ï 3237.

Hydro and Agro Information Institute (HAII). 2013. **The 25 Basin in Thailand**. Available Source: http://www.haii.or.th/wiki/index.php, June 25, 2013

International Standards Organization (ISO). 1997. **Environmental Management: Life Cycle Assessment–Principles and Framework ISO 14040**.

ISO. 1998. **Life Cycle Assessment–Impact Assessment ISO 14042**.

Khongsiri, S. 2009. **Life Cycle Assessment of Cassava Root and Cassava Starch**. M.S. Thesis, Kasetsart University.

Kwanyuen, B., P. Numkhang, W. Phuthongsook and S. Tonwiboonsak. 2010. The study of cassavaôs crop coefficient ($K_c$). *In* **Proceedings of the 11st TSAE Conference: Innovation in Agricultural Engineering for Sufficiency Economy and Empowered Communities**. 6ï 7 May 2010, Nakorn Pathom.

Limpert, E., W.A. Stahel and M. Abbt. 2001. Logï normal Distributions across the Sciences: Keys and Clues. **Bio Science** 51 (5): 341ï 352.

Marta, A.D., M. Mancini, F. Natali, F. Orlando and S. Orlandini. 2012. From water to bioethanol: the impact of climate variability on the water footprint. **Journal of Hydrology** 444ï 445: 180ï 186.

McMahon, T.A.; R.M. Vogel, M.C. Peel and G.G.S. Pegram. 2007. Global streamflows ï Part 1: Characteristics of annual streamflows. **J. Hydrol.** 347: 243ï 259.

Mekonnen, M.M. and A.Y. Hoekstra. 2011. **National water footprint accounts: The green, blue and grey water footprint of production and consumption 1**.

Ministry of Agriculture and Cooperative. 2014. **Ministry of Agriculture and Cooperative Move Forward to Plant 3 Types of Renewable Energy Crops**. Available Source: http://www.moac.go.th/ewt_news.php?nid=2743&filename=fao, June 25, 2014

Narinthapon, P., C. Tiraporn and S. Sindhuprama. 1979. The study of cassava roots treatment**. Report of Experiment of cassava roots of Agricultural Department**. (in Thai). 255.

Office of Agricultural Economics (OAE). 2012. **Agricultural statistics of Thailand 2011. Bangkok, Thailand. Office of Agricultural Economics**. Available Source: http://www.oae.go.th/ewt_news.php?nid=135772013, September 9, 2013.

Pfister, S., A. Koehler, and S. Hellweg. 2009. Assessing the environmental impacts of freshwater consumption in LCA. **Environ. Sci. Technol.** 43: 4098ï 4104.

Piyachomkwan, K. and K. Sriroth. 2005. Transformation and Balance of Cyanogenic Compounds in the Cassava Starch Manufacturing Process. **Starch–Stärke** 57 (2): 71ï 78.

Sriroth K., K. Piyachomkwan, S. Wanlapatit and C.G. Oates. 2000. Cassava Starch Technology: The Thai Experience. **Starch–Stärke** 52 (12): 439ï 449.

Thailand Research Fund. 2014. **Cassava research database**. Available Source: http://kasetinfo.arda.or.th/arda/cassava/?page_id=337, October 27, 2014.

Thai Tapioca Development Institute (TTDI). 2012. **Producers/Exporters**. Available Source: http://www.tapiocathai.org/English/M1_e.html2012, February 1, 2013.

Thai Tapioca Starch Association (TTSA). 2004. **About tapioca & Utility: Tapioca Introduction**. Available Source: http://www.thaitapiocastarch.org/background.asp, September 9, 2013.

TTSA. 2004. **Research & Development: Manufacturing Process Development in Thai Cassava Starch Industry**. Available Source: http://www.thaitapiocastarch.org/article01.asp, September 9, 2013.

United Nations Conference on Trade and Development (UNCTAD). 2012. **Infocomm Commodity Profile Cassava**. Available Source: http://www.unctad.info/en/Infocomm/AACPï Products/COMMODIRYï PROFILEï ï ï Cassava/, February 2, 2013.

UNï Water Statistics. 2009. **Water use**. Available Source: http://www.unwater.org/statistics_use.html, February 18, 2013.

Rickard, J. E. and P. B. Gahan. 1983. The development of occlusions in cassava (Manihot esculenta Crantz.) root xylem vessels. **Annals of Botany** 52: 811ï 821.

# APPENDICES

# Appendix A

Data input and output to CROP WAT 8.0 program

## Data Input of CROP WAT 8.0 program

**Appendix Table A1** Meteorological data of Kanchanaburi province in Tha Chin basin based on 1993ï 2012

| Month | Min Temp (ºC) | Max Temp (ºC) | Humidity (%) | Wind (km/day) | Sun (hours) |
|---|---|---|---|---|---|
| January | 20.4 | 33.1 | 63 | 30 | 30 |
| February | 22.3 | 35.4 | 62 | 35 | 35 |
| March | 24.3 | 36.5 | 63 | 39 | 39 |
| April | 25.7 | 37.6 | 64 | 38 | 38 |
| May | 25.6 | 35.4 | 71 | 31 | 31 |
| June | 25.5 | 34.7 | 71 | 32 | 32 |
| July | 25.1 | 33.7 | 73 | 33 | 33 |
| August | 25 | 33.6 | 74 | 36 | 36 |
| September | 24.6 | 33.4 | 77 | 31 | 31 |
| October | 23.9 | 32.3 | 79 | 26 | 26 |
| November | 22.4 | 31.9 | 71 | 38 | 38 |
| December | 20.3 | 31.6 | 65 | 40 | 40 |
| Average | 23.8 | 34.1 | 69 | 34 | 34 |

**Source**: TMD (2012)

**Appendix Table A2** Meteorological data of Ratchaburi province in Mae Klong basin based on 1993ï 2012

| **Month** | **Min Temp (ºC)** | **Max Temp (ºC)** | **Humidity (%)** | **Wind (km/day)** | **Sun (hours)** |
|---|---|---|---|---|---|
| January | 20 | 32.2 | 67 | 90 | 7.6 |
| February | 21.6 | 34.2 | 67 | 83 | 8.3 |
| March | 23.6 | 35 | 69 | 90 | 7.5 |
| April | 25 | 36.3 | 69 | 83 | 8.2 |
| May | 25.3 | 34.7 | 73 | 83 | 6 |
| June | 25.1 | 33.9 | 75 | 70 | 5 |
| July | 24.8 | 33.2 | 75 | 70 | 4.3 |
| August | 24.8 | 33 | 76 | 77 | 3.8 |
| September | 24.6 | 32.6 | 79 | 77 | 4.2 |
| October | 24.1 | 31.6 | 81 | 77 | 5 |
| November | 22.6 | 31 | 75 | 109 | 6.7 |
| December | 20.5 | 30.7 | 70 | 102 | 7.5 |
| Average | 23.5 | 33.2 | 73 | 84 | 6.2 |

**Source**: TMD (2012)

**Appendix Table A3** Meteorological data of Chonburi province in Bang Pakong basin based on 1993ï 2012

| **Month** | **Min Temp (ºC)** | **Max Temp (ºC)** | **Humidity (%)** | **Wind (km/day)** | **Sun (hours)** |
|---|---|---|---|---|---|
| January | 22.8 | 32.6 | 66 | 64 | 7.5 |
| February | 24.4 | 33.1 | 69 | 61 | 7.8 |
| March | 25.7 | 34 | 71 | 62 | 7.1 |
| April | 26.7 | 35 | 71 | 52 | 7.7 |
| May | 26.6 | 34.3 | 74 | 48 | 5.9 |
| June | 26.6 | 33.8 | 73 | 53 | 4.8 |
| July | 26.5 | 33.3 | 73 | 56 | 4.5 |
| August | 26.2 | 33.1 | 74 | 55 | 5.1 |
| September | 25.4 | 32.6 | 78 | 42 | 4 |
| October | 24.9 | 32.9 | 77 | 46 | 4.9 |
| November | 23.9 | 33.2 | 68 | 69 | 6.8 |
| December | 22.5 | 32.6 | 63 | 75 | 7.2 |
| Average | 25.2 | 33.4 | 71 | 57 | 6.1 |

**Source**: TMD (2012)

**Appendix Table A4** Meteorological data of Nakhon Ratchasima province in Mun basin based on 1993ï 2012

| **Month** | **Min Temp (ºC)** | **Max Temp (ºC)** | **Humidity (%)** | **Wind (km/day)** | **Sun (hours)** |
|---|---|---|---|---|---|
| January | 18.9 | 30.8 | 64 | 56 | 6.7 |
| February | 21.1 | 33.4 | 62 | 51 | 6.6 |
| March | 23.4 | 35.2 | 62 | 55 | 5.4 |
| April | 24.9 | 36.2 | 67 | 51 | 4.2 |
| May | 25.1 | 34.8 | 73 | 57 | 1.9 |
| June | 25.2 | 34.6 | 72 | 70 | 1.9 |
| July | 24.9 | 33.8 | 73 | 72 | 1.9 |
| August | 24.6 | 33.3 | 75 | 66 | 1.9 |
| September | 24.2 | 32.1 | 80 | 47 | 1.8 |
| October | 23.5 | 31.3 | 77 | 65 | 3 |
| November | 21.3 | 30.6 | 70 | 78 | 5.5 |
| December | 18.9 | 29.6 | 65 | 75 | 6.4 |
| Average | 23 | 33 | 70 | 62 | 3.9 |

**Source**: TMD (2012)

**Appendix Table A5** Rainfall in1993ï 2012 of Kanchaburi province in Tha Chin basin (unit: mm)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 1.94 | 0 | 19.68 | 51.5 | 112.06 | 89.06 | 52.5 | 106.76 | 211.26 | 144.88 | 0.12 | 10.32 |
| 1994 | 2.94 | 0.3 | 97.86 | 24.16 | 137.86 | 155.6 | 80.26 | 75.14 | 219.88 | 119.02 | 3.44 | 0.14 |
| 1995 | 0 | 0.06 | 7.12 | 25.74 | 103.56 | 105.98 | 140 | 194.82 | 376.22 | 105.52 | 15.6 | 0.78 |
| 1996 | 1.16 | 1.02 | 13.38 | 76.4 | 129.94 | 132.58 | 116.54 | 113.8 | 349.3 | 171.16 | 73.04 | 0.34 |
| 1997 | 0 | 1.7 | 28.88 | 66.84 | 72.8 | 25.96 | 48.42 | 117.4 | 248.36 | 143.88 | 30.5 | 0.42 |
| 1998 | 0.1 | 21.1 | 0.42 | 33.86 | 108.68 | 128.9 | 170.8 | 111.24 | 224.2 | 267.84 | 94.9 | 9.26 |
| 1999 | 9.96 | 47.34 | 30.22 | 233 | 233.66 | 92.54 | 108.66 | 96.28 | ï 9999 | 342.12 | 87.5 | 5.08 |
| 2000 | 0.66 | 25.18 | 10.82 | 157.3 | 141.24 | 66.58 | 52.88 | 114.4 | 127.84 | 207.94 | 6.16 | 0 |
| 2001 | 4.34 | 1.12 | 103.5 | 2.58 | 144.78 | 90.9 | 95.26 | 82.66 | 165.5 | 242.22 | 21.38 | 3.5 |
| 2002 | 1.76 | 0.28 | 25.5 | 54.1 | 128.82 | 78.4 | 68.08 | 106.26 | 201.12 | 124.98 | 123.6 | 32.08 |
| 2003 | 0 | 8.66 | 93.68 | 38.04 | 102.16 | 154.04 | 148.68 | 88.92 | 239 | 117.14 | 0 | 0 |
| 2004 | 15.82 | 27.7 | 1.96 | 40.24 | 128.94 | 65.14 | 106.92 | 100.82 | 192.02 | 39.66 | 11.32 | 0 |
| 2005 | 6.3 | 2.44 | 46.32 | 37.98 | 108.32 | 81.98 | 98.62 | 82.54 | 365.7 | 203 | 87.66 | 19.54 |
| 2006 | 0.8 | 25.8 | 40.44 | 62.82 | 118.1 | 106.88 | 79.92 | 72.32 | 330.58 | 156.64 | 8.26 | 5.96 |
| 2007 | 6.26 | 0.18 | 5.16 | 98.3 | 224.66 | 114.08 | 109.12 | 98.74 | 111.62 | 160.36 | 14 | 2.9 |

**Appendix Table A5** (Continued)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2008 | 0.74 | 56.42 | 17.98 | 75.18 | 167.5 | 167.44 | 104.32 | 119.98 | 183.7 | 198.3 | 44.38 | 0 |
| 2009 | 0.2 | 1.08 | 29.08 | 55 | 210.98 | 94.46 | 87.56 | 118.14 | 189.22 | 230.26 | 3.66 | 0 |
| 2010 | 5.92 | 1.68 | 10.56 | 13.38 | 69.54 | 159.9 | 123.26 | 200.48 | 249.42 | 308.42 | 0.2 | 19.46 |
| 2011 | 0.04 | 8.62 | 108.8 | 74.22 | 159.42 | 102.2 | 125.66 | 134.76 | 188.28 | 216.5 | 0.34 | 0 |
| 2012 | 6.34 | 16.68 | 16.8 | 40.04 | 125.6 | 61.76 | 133.12 | 81.96 | 415.98 | 151.18 | 75.48 | 0 |

**Source**: TMD (2012)

**Appendix Table A6** Rainfall in1993ï 2012 of Ratchaburi province in Maeï klong basin (unit: mm)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 1.6 | 0 | 37.52 | 43.8 | 142.9 | 103.56 | 115 | 156.4 | 294.64 | 135.96 | 4.96 | 8.3 |
| 1994 | 0 | 4.92 | 73.46 | 37.66 | 248.74 | 186.12 | 314.82 | 195.22 | 218.36 | 107.6 | 12.04 | 2.76 |
| 1995 | 1.56 | 0.06 | 39.08 | 36.92 | 156.5 | 170.76 | 179.66 | 278.9 | 300.36 | 149.98 | 36.84 | 0.96 |
| 1996 | 0 | 19.98 | 10.44 | 113.24 | 155.34 | 199.42 | 282.18 | 189.62 | 395.14 | 188.92 | 62.84 | 0.98 |
| 1997 | 0 | 0.08 | 19.16 | 41.48 | 76.08 | 84.66 | 242.38 | 267.04 | 230.4 | 138.34 | 95.2 | 0 |
| 1998 | 0 | 3.7 | 1.16 | 8.62 | 177.08 | 145.04 | 168.98 | 143.82 | 175.52 | 190.98 | 65.68 | 3 |
| 1999 | 12.58 | 11.34 | 29.42 | 200.14 | 255.66 | 137.96 | 118 | 205.88 | ï 9999 | 298.52 | 73.52 | 2.42 |
| 2000 | 0.7 | 38.48 | 26.64 | 204.18 | 192 | 174.96 | 113.92 | 145.38 | 211.48 | 279.96 | 4.96 | 0.4 |
| 2001 | 13.76 | 5.08 | 126.56 | 25.58 | 234.86 | 153.68 | 144.48 | 159.2 | 182.4 | 233.54 | 27.84 | 9.72 |
| 2002 | 2.26 | 1.78 | 20.9 | 93.6 | 224.66 | 111.74 | 139.36 | 207.66 | 350.26 | 131.54 | 96.98 | 15.76 |
| 2003 | 2.44 | 7.08 | 104.66 | 60.08 | 110.64 | 186.3 | 252.74 | 168.04 | 240.94 | 120.4 | 0.88 | 0 |
| 2004 | 7.92 | 12.58 | 7.74 | 44.3 | 267.06 | 185.66 | 94.14 | 139.68 | 245.9 | 45.24 | 1.76 | 0 |
| 2005 | 1.44 | 2.9 | 24.8 | 74 | 137.72 | 146.84 | 221.42 | 148.56 | 271.7 | 194.42 | 32.96 | 23.52 |
| 2006 | 0.28 | 28.62 | 65.4 | 120.94 | 281.3 | 160.92 | 215.12 | 180.26 | 272.54 | 157.4 | 18.24 | 2.5 |
| 2007 | 3.02 | 0.08 | 19.46 | 92.32 | 315.46 | 140.72 | 163.08 | 175.24 | 214.42 | 207.08 | 22.7 | 0 |

**Appendix Table A6** (Continued)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2008 | 0.18 | 47 | 33.8 | 166.46 | 185.56 | 142.36 | 143.44 | 155.74 | 183.02 | 253.28 | 48.88 | 6.02 |
| 2009 | 0.04 | 4.26 | 97.8 | 75.44 | 227.96 | 157.76 | 207.46 | 219.2 | 185.74 | 220.3 | 6.8 | 0 |
| 2010 | 17.5 | 1.7 | 10.7 | 39.96 | 96.88 | 146.48 | 236.42 | 226.78 | 236.04 | 264.26 | 0.96 | 20.78 |
| 2011 | 4.02 | 17.62 | 147.24 | 109.32 | 198.88 | 158.92 | 219.84 | 192.36 | 192.3 | 202.8 | 0.48 | 1.68 |
| 2012 | 12.1 | 22.96 | 41.9 | 39.66 | 189.1 | 155.14 | 235.84 | 179.52 | 366.74 | 103.7 | 86.88 | 1.12 |

**Source**: TMD (2012)

**Appendix Table A7** Rainfall in1993ï 2012 of Chonburi province in Ban Pakong basin (unit: mm)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 12.30 | 5.17 | 54.73 | 54.30 | 156.07 | 109.40 | 80.07 | 301.83 | 259.23 | 196.83 | 2.13 | 2.73 |
| 1994 | 0.00 | 1.93 | 87.77 | 101.73 | 235.00 | 324.17 | 73.23 | 142.30 | 250.57 | 146.33 | 10.37 | 17.23 |
| 1995 | 12.97 | 2.77 | 40.93 | 52.53 | 186.50 | 129.23 | 159.17 | 320.93 | 369.50 | 219.57 | 28.83 | 2.33 |
| 1996 | 13.60 | 30.07 | 33.33 | 115.20 | 200.97 | 156.63 | 205.70 | 103.97 | 327.27 | 188.07 | 68.77 | 0.43 |
| 1997 | 26.57 | 5.73 | 37.70 | 94.37 | 60.37 | 118.33 | 56.57 | 85.70 | 406.80 | 199.73 | 16.30 | 0.00 |
| 1998 | 24.63 | 33.60 | 30.20 | 70.70 | 146.23 | 173.10 | 219.03 | 250.97 | 323.30 | 181.33 | 39.50 | 0.23 |
| 1999 | 13.67 | 32.30 | 68.90 | 236.03 | 247.33 | 84.63 | 104.70 | 133.37 | ï 9999 | 357.37 | 101.00 | 0.27 |
| 2000 | 0.00 | 53.17 | 45.37 | 180.43 | 224.60 | 174.33 | 155.03 | 155.70 | 276.77 | 174.67 | 6.63 | 1.10 |
| 2001 | 1.23 | 9.87 | 135.73 | 44.27 | 232.43 | 145.17 | 63.27 | 157.93 | 220.20 | 253.73 | 61.47 | 10.10 |
| 2002 | 7.43 | 21.27 | 32.17 | 79.43 | 199.53 | 176.97 | 87.00 | 170.93 | 215.77 | 162.50 | 87.40 | 36.53 |
| 2003 | 0.00 | 35.13 | 242.70 | 43.40 | 157.07 | 191.53 | 162.90 | 207.53 | 282.00 | 141.53 | 0.00 | 0.00 |
| 2004 | 41.07 | 66.33 | 36.10 | 55.43 | 115.00 | 151.80 | 210.97 | 157.93 | 259.33 | 58.73 | 0.17 | 0.00 |
| 2005 | 19.90 | 1.97 | 49.37 | 126.23 | 124.37 | 100.53 | 115.93 | 103.50 | 357.97 | 166.40 | 164.53 | 19.47 |
| 2006 | ï 3332.77 | 15.87 | 60.87 | 89.30 | 187.73 | 149.57 | 156.13 | 162.10 | 357.67 | 203.37 | 14.93 | 1.60 |

**Appendix Table A7** (Continued)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2007 | 1.67 | 7.93 | 68.03 | 220.90 | 246.80 | 230.43 | 249.97 | 84.83 | 213.03 | 153.10 | 20.90 | 0.00 |
| 2008 | 4.63 | 45.07 | 32.90 | 184.83 | 138.60 | 163.87 | 251.87 | 207.77 | 325.33 | 227.43 | 48.10 | 0.20 |
| 2009 | 0.00 | 0.13 | 109.87 | 136.23 | 231.63 | 134.93 | 152.90 | 191.33 | 351.50 | 230.30 | 37.70 | 10.53 |
| 2010 | 34.97 | 22.33 | 30.43 | 69.20 | 169.30 | 176.70 | 271.73 | 308.83 | 336.50 | 215.77 | 7.73 | 30.27 |
| 2011 | 0.67 | 39.37 | 104.67 | 126.60 | 223.07 | 242.60 | 190.13 | 395.77 | 311.77 | 201.40 | 7.03 | 1.37 |
| 2012 | 37.30 | 10.47 | 78.37 | 66.03 | 121.33 | 125.10 | 186.03 | 129.47 | 428.87 | 229.10 | 94.97 | 1.07 |

**Source**: TMD (2012)

**Appendix Table A8** Rainfall in1993ï 2012 of Nakhon Ratchasima province in Mun basin (unit: mm)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 0.65 | 5.34 | 51.39 | 97.25 | 186.56 | 131.14 | 177.05 | 137.55 | 228.20 | 69.31 | 0.21 | 6.59 |
| 1994 | 0.01 | 48.27 | 64.39 | 50.43 | 233.62 | 197.25 | 80.11 | 247.93 | 258.21 | 80.09 | 7.45 | 4.33 |
| 1995 | 0.34 | 14.55 | 32.84 | 61.12 | 170.94 | 154.40 | 260.95 | 185.63 | 236.85 | 112.79 | 20.20 | 0.20 |
| 1996 | 0.74 | 5.45 | 29.08 | 122.46 | 177.75 | 203.63 | 111.00 | 172.96 | 358.17 | 115.56 | 87.92 | 0.05 |
| 1997 | 0.46 | 13.40 | 59.08 | 80.35 | 173.69 | 162.94 | 243.26 | 206.41 | 149.78 | 109.09 | 4.70 | 0.00 |
| 1998 | 0.51 | 30.91 | 17.40 | 77.19 | 197.61 | 152.25 | 138.22 | 210.32 | 219.43 | 101.57 | 75.57 | 2.73 |
| 1999 | 4.99 | 7.08 | 89.52 | 150.26 | 208.85 | 171.93 | 220.76 | 112.81 | ï 9999 | 140.50 | 38.98 | 1.03 |
| 2000 | 11.28 | 28.59 | 8.68 | 204.93 | 303.08 | 282.36 | 231.17 | 355.56 | 189.10 | 96.22 | 5.22 | 0.00 |
| 2001 | 2.28 | 6.23 | 93.75 | 33.20 | 178.70 | 240.84 | 160.19 | 265.60 | 218.20 | 183.85 | 48.38 | 0.43 |
| 2002 | 0.08 | 10.55 | 39.37 | 72.29 | 148.22 | 185.20 | 188.51 | 311.55 | 357.79 | 92.97 | 21.05 | 17.95 |
| 2003 | 0.00 | 32.02 | 88.47 | 67.31 | 158.25 | 181.41 | 124.48 | 261.39 | 292.81 | 71.36 | 0.14 | 0.00 |
| 2004 | 24.06 | 38.31 | 13.13 | 73.19 | 182.98 | 274.86 | 288.91 | 177.18 | 180.01 | 2.62 | 5.78 | 0.00 |
| 2005 | 1.68 | 0.88 | 27.03 | 65.37 | 186.73 | 138.82 | 235.20 | 208.60 | 266.62 | 78.88 | 68.25 | 3.20 |
| 2006 | 0.06 | 14.14 | 49.98 | 110.43 | 157.77 | 150.59 | 241.62 | 256.18 | 171.45 | 225.88 | 18.34 | 0.80 |
| 2007 | 0.56 | 18.69 | 54.69 | 71.87 | 269.43 | 129.20 | 188.57 | 292.03 | 226.73 | 199.38 | 10.94 | 0.00 |

**Appendix Table A8** (Continued)

| **Year/ Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2008 | 0.70 | 4.54 | 32.55 | 123.07 | 264.32 | 127.93 | 109.92 | 178.57 | 380.73 | 142.58 | 46.77 | 3.91 |
| 2009 | 0.00 | 14.51 | 92.12 | 139.27 | 170.01 | 138.54 | 268.13 | 205.84 | 311.42 | 79.78 | 6.02 | 1.20 |
| 2010 | 30.64 | 14.97 | 14.65 | 75.69 | 106.09 | 136.17 | 212.64 | 296.00 | 228.55 | 230.83 | 2.42 | 6.35 |
| 2011 | 0.07 | 17.47 | 20.55 | 93.80 | 203.74 | 144.46 | 204.78 | 275.46 | 357.98 | 213.00 | 2.64 | 0.12 |
| 2012 | 45.81 | 6.09 | 27.33 | 86.61 | 219.85 | 82.56 | 126.02 | 243.64 | 231.36 | 62.26 | 54.26 | 0.52 |

**Source**: TMD (2012)

**Appendix Table A9** Crop data of Kanchanaburi, Ratchaburi, Chonburi and Nakhon Ratchasima provinces in Tha Chin, Mae Klong, Bang Pakong and Mun basins, respectively.

| **Crop Name: cassava** | | **Planting date: 01/04** | | **Harvest: 27/10** | |
|---|---|---|---|---|---|
| **Stage** | **initial** | **develop** | **mid** | **late** | **total** |
| Length (days) | 20 | 40 | 90 | 60 | 210 |
| $K_c$ Values | 0.35 | ï ï > | 1.04 | 0.5 | |
| Rooting depth (m) | 0.5 | ï ï > | 0.8 | 0.8 | |
| Critical depletion | 0.35 | ï ï > | 0.35 | 0.35 | 1 |
| Yield response f. | 1 | 1 | 1 | 1 | |
| Crop height (m) | | | 3 | | |

**Appendix Table A10** The $ET_c$ and $P_{eff}$ of Kanchanaburi province in Tha Chin basin

| month | period (decade) | stage | $ET_c$ (mm/decade) | $P_{eff}$ (mm/decade) |
|---|---|---|---|---|
| Apr | 1 | Init | 15.7 | 20.6 |
| Apr | 2 | Init | 16.1 | 23 |
| Apr | 3 | Deve | 17.8 | 28.1 |
| May | 1 | Deve | 21.1 | 36 |
| May | 2 | Deve | 23.6 | 42 |
| May | 3 | Mid | 30.4 | 36.8 |
| Jun | 1 | Mid | 28.6 | 28.8 |
| Jun | 2 | Mid | 27.6 | 24.1 |
| Jun | 3 | Mid | 27.5 | 25.9 |
| Jul | 1 | Mid | 27.3 | 28.7 |
| Jul | 2 | Mid | 27.2 | 30 |
| Jul | 3 | Mid | 29.9 | 29.6 |
| Aug | 1 | Mid | 27.2 | 27.1 |
| Aug | 2 | Mid | 27.1 | 25.9 |
| Aug | 3 | Late | 29.2 | 33.8 |
| Sep | 1 | Late | 24 | 45.2 |
| Sep | 2 | Late | 21 | 53.4 |
| Sep | 3 | Late | 18.1 | 50.4 |
| Oct | 1 | Late | 15.3 | 48.5 |
| Oct | 2 | Late | 12.7 | 47.9 |
| Oct | 3 | Late | 7.9 | 23.1 |

**Appendix Table A11** The $ET_c$ and $P_{eff}$ of Ratchaburi province in Mae Klong basin

| month | period (decade) | stage | $ET_c$ (mm/decade) | $P_{eff}$ (mm/decade) |
|---|---|---|---|---|
| Apr | 1 | Init | 17.8 | 10.5 |
| Apr | 2 | Init | 18.5 | 10.3 |
| Apr | 3 | Deve | 21.5 | 20.1 |
| May | 1 | Deve | 26.9 | 34.1 |
| May | 2 | Deve | 31.9 | 44.3 |
| May | 3 | Mid | 41 | 40.6 |
| Jun | 1 | Mid | 38.4 | 34.7 |
| Jun | 2 | Mid | 37 | 32.3 |
| Jun | 3 | Mid | 36.2 | 33 |
| Jul | 1 | Mid | 35.5 | 34.5 |
| Jul | 2 | Mid | 34.8 | 35.1 |
| Jul | 3 | Mid | 37.9 | 34.1 |
| Aug | 1 | Mid | 34.1 | 31.2 |
| Aug | 2 | Mid | 33.8 | 29.5 |
| Aug | 3 | Late | 36.8 | 35.8 |
| Sep | 1 | Late | 30.8 | 44.2 |
| Sep | 2 | Late | 27.4 | 50.3 |
| Sep | 3 | Late | 23.8 | 50.1 |
| Oct | 1 | Late | 20.4 | 52.6 |
| Oct | 2 | Late | 17 | 54.7 |
| Oct | 3 | Late | 10.2 | 26.6 |

**Appendix Table A12** The $ET_c$ and $P_{eff}$ of Chonburi province in Bang Pakong basin

| month | period<br>(decade) | stage | $ET_c$<br>(mm/decade) | $P_{eff}$<br>(mm/decade) |
|---|---|---|---|---|
| Apr | 1 | Init | 16.6 | 20 |
| Apr | 2 | Init | 17.2 | 20.6 |
| Apr | 3 | Deve | 19.9 | 27.5 |
| May | 1 | Deve | 24.9 | 37.4 |
| May | 2 | Deve | 29.6 | 44.7 |
| May | 3 | Mid | 38.1 | 42.2 |
| Jun | 1 | Mid | 35.9 | 38.2 |
| Jun | 2 | Mid | 34.9 | 36.6 |
| Jun | 3 | Mid | 34.6 | 36.2 |
| Jul | 1 | Mid | 34.3 | 35.4 |
| Jul | 2 | Mid | 34.1 | 34.6 |
| Jul | 3 | Mid | 38 | 36.6 |
| Aug | 1 | Mid | 35 | 38.4 |
| Aug | 2 | Mid | 35.5 | 39.9 |
| Aug | 3 | Late | 37.1 | 43.7 |
| Sep | 1 | Late | 29.7 | 49.3 |
| Sep | 2 | Late | 25.2 | 53.7 |
| Sep | 3 | Late | 22.1 | 50.4 |
| Oct | 1 | Late | 19.1 | 48.4 |
| Oct | 2 | Late | 16 | 47.1 |
| Oct | 3 | Late | 9.7 | 22.5 |

**Appendix Table A13** The $ET_c$ and $P_{eff}$ of Nakhon Ratchasima in Mun basin

| month | period (decade) | stage | $ET_c$ (mm/decade) | $P_{eff}$ (mm/decade) |
|---|---|---|---|---|
| Apr | 1 | Init | 13.6 | 21.9 |
| Apr | 2 | Init | 13.5 | 25.6 |
| Apr | 3 | Deve | 15.7 | 30.4 |
| May | 1 | Deve | 19.7 | 37.3 |
| May | 2 | Deve | 23.1 | 43 |
| May | 3 | Mid | 31 | 39.2 |
| Jun | 1 | Mid | 30.3 | 33.3 |
| Jun | 2 | Mid | 30.5 | 30 |
| Jun | 3 | Mid | 30.4 | 31 |
| Jul | 1 | Mid | 30.3 | 31.9 |
| Jul | 2 | Mid | 30.2 | 32.1 |
| Jul | 3 | Mid | 32.9 | 35 |
| Aug | 1 | Mid | 29.6 | 38.2 |
| Aug | 2 | Mid | 29.3 | 40.9 |
| Aug | 3 | Late | 31 | 43.2 |
| Sep | 1 | Late | 25 | 47.4 |
| Sep | 2 | Late | 21.5 | 50.7 |
| Sep | 3 | Late | 19.2 | 45.4 |
| Oct | 1 | Late | 16.8 | 40.5 |
| Oct | 2 | Late | 14.3 | 36.9 |
| Oct | 3 | Late | 8.7 | 17.1 |

# Appendix B

## Examples of Calculation

**Example 1** Calculation ET$_{green}$ and CWU$_{green}$

Use data from Appendix Table A10

From The equation below

$$ET_{green} = \min(ET_c, P_{eff})\,[\text{length/time}]$$

Where:

P$_{eff}$ = effective rainfall

ET$_c$ = and evapotranspiration of cassava

Therefore:

ET$_{green}$ of Aprï 01 = 15.7 mm/decade

From The equation below

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green}\ [\text{volume/area}]$$

Therefore:

$$\sum_{d=1}^{lgp} ET_{green} = 15.7 + 16.1 + 17.8 + ... + 7.9$$

$$= 468.6 \text{ mm/year}$$

$$CWU_{green} = 10 \times 468.6\ (m^3/ha)$$

$$= 4686\ (m^3/ha)$$

**Example 2** Calculation ET$_{blue}$ and CWU$_{blue}$

Use data from Appendix Table A10

From The equation below

$$ET_{blue} = \max(0, ET_c - P_{eff})\,[\text{length/time}]$$

Where:

P$_{eff}$ = effective rainfall

ET$_c$ = and evapotranspiration of cassava

Therefore:

ET$_{blue}$ of Aprï 01 = 0 mm/decade

From The equation below

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \ [volume/area]$$

Therefore:

$$\sum_{d=1}^{lgp} ET_{blue} = 0+0+0+0+0+0+0+0+3.5+...+0$$

$$= 6.7 \ mm/year$$

$$CWU_{blue} = 10 \times 6.7 \ (m^3/ha)$$

$$= 67 \ (m^3/ha)$$

**Example 3** Calculation $WF_{green}$

$$WF_{procgreen} = \frac{CWU_{green}}{Y} \ [volume/mass]$$

Where:

$WF_{green}$ = the green water footprint

$CWU_{green}$ = the crop water use ($m^3$/ha)

Y = the crop yield (ton/ha)

Therefore:

$WF_{green}$ = 4686 ($m^3$/ha)/ 19.33 (ton/ha)

= 242.4 ($m^3$/ton of root)

**Example 4** Calculation $WF_{blue}$

$$WF_{proc, blue} = \frac{CWU_{blue}}{Y} \ [volume/mass]$$

Where:

$WF_{blue}$ = the blue water footprint

$CWU_{blue}$ = the crop water use ($m^3$/ha)

Y = the crop yield (ton/ha)

Therefore:

$WF_{blue}$ = 67 ($m^3$/ha)/ 19.33 (ton/ha)

= 3.5 ($m^3$/ton of root)

**Example 5** Calculation Water availability (unit: 1 ton of starch)

The water availability of cassava starch production use in term Effective rainfall ($Rain_{eff}$).

$Rain_{eff}$ of Kanchanaburi = 1097.2 mm

Therefore:

$Rain_{eff}$ = (1,097.2 mm/1,000) × (10,000/ha)
= 10,972 $m^3$/ha
= 10,972 $m^3$/ha × (0.224366 ha/ 1 ton of starch)
= 2461.747 $m^3$/ 1 ton of starch

**Example 6** Calculation the seasonal variation factor (VF) by Method 1 according to Pfister *et al*. (2009)

Calculation of VF from rainfall of Ratchaburi province data see in Appendix Table A6. It was separated into 6 steps as shown below.

1. Calculation monthly mean of 12 month and yearly totals Monthly

Mean of month 1 = (8+0+0+0+é +13.2)/20 mm
= 2.115 mm
Yearly total in 1993 = 8+0+53.2+24.5
= 1002.7 mm

2. Logï transform the rainfall data of Ratchaburi (the mean monthly and the yearly totals.

Mean monthly of month 1 = log2.115
= 1.0349
Yearly total in 1993 = log 1002.7
= 6.91

Logï transform data in Appendix Table A6 and show in Appendix Table B1

**Appendix Table B1** The mean monthly Logï transformed and monthly standard deviation of Ratchaburi province

| **Month** | **Mean monthly** | **Standard deviation of monthly** |
|---|---|---|
| 1 | 1.035 | 1.280 |
| 2 | 1.961 | 1.725 |
| 3 | 2.822 | 1.378 |
| 4 | 2.926 | 1.758 |
| 5 | 4.931 | 0.612 |
| 6 | 4.664 | 0.687 |
| 7 | 4.731 | 0.572 |
| 8 | 4.664 | 0.552 |
| 9 | 5.345 | 0.437 |
| 10 | 5.431 | 0.415 |
| 11 | 3.512 | 1.337 |
| 12 | 2.083 | 1.193 |

3. Calculate the standard deviation ($s_{month}$) of the monthly averages of the Logï transformed data

$$s_{month} = \frac{\sqrt{\sum\left(x-\bar{x}\right)^2}}{(n-1)}$$

Where:

$\bar{x}$ = the mean of sample

n = the sample size

Therefore:

$$s_{month} = \frac{\sqrt{(1.035-3.675)^2 + (1.961-3.675)^2 + (2.822-3.675)^2 + (2.083-3.675)^2}}{(12-1)}$$

$= 1.485$

4. Calculate the standard deviation (sï year) of the Logï transformed the

yearly totals

$$s_{year} = \frac{\sqrt{\sum\left(x-\bar{x}\right)^2}}{\left(n-1\right)}$$

Where:

$\bar{x}$ = the mean of sample

n = the sample size

Therefore:

$$s_{year} = \frac{\sqrt{\left(6.910-7.033\right)^2 + \left(6.860-7.033\right)^2 + \left(7.242-7.033\right)^2 + \left(6.936-7.033\right)^2}}{\left(20-1\right)}$$

$= 0.148$

5. Calculate standard deviations of the Logï transformed monthly average ($s^*_{month}$) and yearly totals ($s^*_{year}$)

$s^*_{month}$ = EXP ($s_{month}$)

$= e^{1.485}$

$= 4.42$

$s^*_{year}$ = EXP ($s_{year}$)

$= e^{0.148}$

$= 1.16$

6. Calculate the seasonal variation factor (VF)

Calculate VF from equation

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

$$VF = e^{\sqrt{\ln\left(4.42\right)^2 + \ln\left(1.16\right)^2}}$$

$= 4.45$

Calculate VFï SRF

VFï SRF = $\sqrt{VF}$

$= \sqrt{4.45}$

= 2.11

**Example 7** Calculation of the seasonal variation factor (VF) by Method 2 (use the equation proposed by Limpert *et al*. in 2001 to calculate $s^*_{month}$ and $s^*_{year}$ directly)

Calculation of VF from rainfall of Ratchaburi province data see in Appendix Table A6. It separated into 5 steps as shown below.

1. Calculation the monthly mean of 12 month

The monthly mean of month 1 = (8+0+0+0+é  +13.2)/20 mm

= 2.115 mm

2. Calculation the monthly average ($m_{month}$) and the standard deviation ($s_{month}$) of monthly mean of 12 month.

$m_{month}$ = (2.115+6.07+34.995+é  +8.55)/12

= 96.427

The standard deviation ($s_{month}$) of monthly mean of 12 month calculated from equation below

$$s_{month} = \frac{\sqrt{\sum\left(x-\bar{x}\right)^2}}{\left(n-1\right)}$$

Where:

$\bar{x}$ = the mean of sample

n = the sample size

Therefore:

$$s_{month} = \frac{\sqrt{\left(2.115-96.426\right)^2+\left(16.07-96.426\right)^2+\left(34.99-96.426\right)^2+\ldots+\left(8.55-96.426\right)^2}}{\left(12-1\right)}$$

= 84.991

3. Calculate the average yearly total ($m_{year}$) and standard deviation ($s_{year}$) of the yearly total rainfall.

$m_{year}$ = (1,002.7 +953.5+1,396.2+é +1,028.3)/20 mm

= 1145.735 mm

The standard deviation ($s_{year}$) of the yearly total rainfall calculate as equation below

$$s_{year} = \frac{\sqrt{\sum\left(x-\bar{x}\right)^2}}{\left(n-1\right)}$$

Where:

$\bar{x}$ = the mean of sample

n = the sample size

Therefore:

$$s_{year} = \frac{\sqrt{\left(1{,}002.7-1{,}145.735\right)^2+(953.5-1{,}145.735)^2+\ldots+\left(1{,}028.3-1{,}145.735\right)^2}}{\left(20-1\right)}$$

=173.179

4. Calculate $s^*_{month}$ and $s^*_{year}$

Calculation $s^*_{month}$ from equation below

$$s^*_{month} = e^{\sqrt{\ln\left(\frac{s}{m}\right)^2+1}}$$

Where:

s = the standard deviation of monthly average

m = the monthly average

Therefore:

$$s^*_{month} = e^{\sqrt{\ln\left(\frac{84.991}{96.426}\right)^2+1}}$$

= 1.333

Calculation $s^*_{year}$ from equation below

$$s^*_{year} = e^{\sqrt{\ln\left(\frac{s}{m}\right)^2+1}}$$

Where:

s = the standard deviation of the yearly total

m = the average yearly total

Therefore:

$$s^*_{year} = e^{\sqrt{\ln\left(\frac{173.1791}{1145.735}\right)^2+1}}$$

$$= 1.011$$

5. Calculate standard variation (VF)

Calculate VF value from equation

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

$$VF = e^{\sqrt{\ln(1.333)^2+\ln(1.011)^2}}$$

$$= 1.33$$

Calculate VFï SRF value

$$VFï\ SRF = \sqrt{VF}$$

$$= \sqrt{1.33}$$

$$= 1.15$$

**Example 8** Calculation of seasonal variation factor (VF) by Method 3

Calculation of VF from rainfall of Ratchaburi province data is presented in Appendix Table A6. It was separated into 8 steps as shown below.

1. Calculation all of 12 month of the monthly average of rainfall data in Ratchaburi.

Monthly average of month 1 = (8+0+0+0+é +13.2)/20 mm

= 2.115 mm

2. Logï transform the monthly averages of the rainfall data in Ratchaburi

Monthly average = log 2.115

= 1.035

3. Calculate the standard deviation ($s_{month}$) of the monthly averages of the Logï transformed data

Calculate the standard deviation ($s_{month}$) from the equation below

$$s_{month} = \frac{\sqrt{\sum\left(x-\bar{x}\right)^2}}{\left(n-1\right)}$$

Where:

$\bar{x}$ = the mean of sample

n = the sample size

Therefore:

$$s_{month} = \frac{\sqrt{\left(1.035-3.675\right)^2+\left(1.961-3.675\right)^2+\left(2.822-3.675\right)^2+\left(2.083-3.675\right)^2}}{\left(12-1\right)}$$

= 1.485

4. Calculate yearly totals of the rainfall data in Ratchaburi

Yearly total in 1993 = 8+0+53.2+é  +24.5

= 1002.7

Yearly totals average = (1,002.7 +953.5+1,396.2+é  +1,028.3)/20 mm

= 1145.735

5. Logï transform the yearly totals of the rainfall data in Ratchaburi

Yearly total in 1993 = log1002.7

= 6.910

*The other Logï transform yearly totals of rain fall shown in Appendix Table B3

6. Calculate the average yearly total ($m_{year}$) and standard deviation ($s_{year}$) of the Logï transformed yearly totals

$m_{year}$ = (1,002.7 +953.5+1,396.2+é  +1,028.3)/20 mm

= 1145.735 mm

The standard deviation (sï year) of the yearly total rainfall calculate as equation below

$$s_{year} = \frac{\sqrt{\sum\left(x-\bar{x}\right)^2}}{\left(n-1\right)}$$

Where:

$\bar{x}$ = the mean of sample

n = the sample size

Therefore:

$$s_{year} = \frac{\sqrt{(1,002.7-1,145.735)^2+(953.5-1,145.735)^2+\ldots+(1,028.3-1,145.735)^2}}{(20-1)}$$

$= 173.179$

7. Calculate $s^*_{month}$ and $s^*_{year}$

$s^*_{month} = \text{EXP}(s_{month})$

$= e^{1.485}$

$= 4.71$

Calculation $s^*_{year}$ from equation below

$s^*_{year} = \text{EXP}\ (s_{year})$

$= e^{0.148}$

$= 1.16$

8. Calculate the seasonal variation factor (VF)

Calculate VF from equation below

$$\text{VF} = e^{\sqrt{\ln(s^*_{month})^2+\ln(s^*_{year})^2}}$$

$$\text{VF} = e^{\sqrt{\ln(4.71)^2+\ln(1.16)^2}}$$

$= 4.74$

Calculate VFï SRF value

VFï SRF = $\sqrt{\text{VF}}$

$= \sqrt{4.74}$

$= 2.18$

**Appendix Table B2** The logï transformed rainfall data in1993ï 2012 of Ratchaburi province in Mae Klong basin (unit: mm)

| Year/ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 2.079 |  | 3.974 | 2.434 | 4.805 | 4.718 | 4.086 | 4.954 | 5.314 | 5.495 | 3.161 | 3.199 |
| 1994 |  |  | 4.253 |  | 5.493 | 4.919 | 4.436 | 4.397 | 5.511 | 4.386 |  | 2.282 |
| 1995 |  |  | 4.024 |  | 5.048 | 5.150 | 5.317 | 5.213 | 5.918 | 5.400 | 3.453 |  |
| 1996 |  | 2.485 | 2.885 | 4.938 | 5.220 | 5.234 | 5.162 | 4.705 | 5.928 | 5.521 | 4.176 | 1.411 |
| 1997 |  |  | 0.693 | 3.714 | 3.077 | 4.142 | 3.867 | 4.459 | 5.817 | 5.834 | 5.854 |  |
| 1998 |  | 2.054 | 0.642 | 0.531 | 4.907 | 5.545 | 5.699 | 5.127 | 5.532 | 5.109 | 4.050 | 2.197 |
| 1999 | 0.470 | 2.175 | 1.946 | 5.061 | 5.697 | 4.797 | 4.300 | 4.783 | n/a | 5.636 | 4.031 | 0.336 |
| 2000 | ï 1.609 | 2.773 | 2.845 | 5.029 | 4.412 | 4.355 | 3.972 | 4.760 | 4.697 | 6.005 | 1.872 |  |
| 2001 |  |  | 5.248 | 1.988 | 5.478 | 4.563 | 4.999 | 3.437 | 5.738 | 5.686 | 3.346 | 0.262 |
| 2002 |  |  | 3.219 | 1.131 | 4.817 | 5.274 | 3.807 | 4.717 | 5.481 | 5.206 | 4.813 | 2.901 |
| 2003 |  |  | 3.321 | 3.001 | 4.731 | 5.027 | 5.360 | 5.214 | 5.395 | 5.662 |  |  |
| 2004 | 1.723 | 2.389 | 2.389 | 2.380 | 5.391 | 4.055 | 4.109 | 4.241 | 5.842 | 5.157 | 1.386 |  |
| 2005 | 1.872 |  | 2.262 | ï 0.105 | 4.468 | 4.653 | 4.947 | 4.743 | 4.982 | 6.090 | 3.666 | 4.072 |
| 2006 |  | 2.885 | 2.580 | 4.121 | 5.311 | 5.202 | 4.418 | 3.190 | 5.015 | 5.369 |  | 2.241 |

**Appendix Table B2** (Continued)

| Year/ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2007 | 0.095 | | ï 0.105 | 4.506 | 5.815 | 4.677 | 4.890 | 5.386 | 5.312 | 4.767 | 4.352 | |
| 2008 | | 3.780 | 1.668 | 4.349 | 4.572 | 5.130 | 4.777 | 4.575 | 4.415 | 5.642 | 3.493 | 0.788 |
| 2009 | | | 4.602 | 3.544 | 4.954 | 4.696 | 5.142 | 4.673 | 5.085 | 5.491 | 3.100 | |
| 2010 | 0.693 | ï 2.303 | 3.059 | 2.588 | 4.263 | 4.992 | 5.525 | 5.221 | 5.282 | 5.675 | 0.588 | 3.178 |
| 2011 | 1.411 | 1.411 | 3.916 | 3.965 | 4.901 | 3.624 | 4.949 | 4.600 | 4.706 | 5.589 | | 2.128 |
| 2012 | 2.580 | | 3.025 | ï 0.511 | 5.266 | 2.518 | 4.851 | 4.882 | 5.576 | 4.907 | 4.857 | |

**Appendix Table B3** The total per year of rainfall and logï transformed total per year of rainfall data in1993ï 2012 of Ratchaburi province (unit: mm)

| **Year** | **Total per year** | **Log-transformed Total per year** |
|---|---|---|
| 1993 | 1002.7 | 6.910 |
| 1994 | 953.5 | 6.860 |
| 1995 | 1396.2 | 7.242 |
| 1996 | 1521.5 | 7.327 |
| 1997 | 1288.3 | 7.161 |
| 1998 | 1354.4 | 7.211 |
| 1999 | 1125.5 | 7.026 |
| 2000 | 1037.9 | 6.945 |
| 2001 | 1346.9 | 7.206 |
| 2002 | 1067.3 | 6.973 |
| 2003 | 1218.2 | 7.105 |
| 2004 | 968.1 | 6.875 |
| 2005 | 1149.8 | 7.047 |
| 2006 | 959 | 6.866 |
| 2007 | 1284.5 | 7.158 |
| 2008 | 1007.9 | 6.916 |
| 2009 | 1089.7 | 6.994 |
| 2010 | 1205 | 7.094 |
| 2011 | 910 | 6.813 |
| 2012 | 1028.3 | 6.936 |

**Example 9 WSI Calculation of Ratchaburi province in Mae–Klong Basin**

WSI calculation of Maeï Klong basin is separated into three step as shown below.

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

1. WTA Calculation from equation below

$$\mathrm{WTA} = \frac{\mathrm{WU}}{\mathrm{WA}}$$

Where:

WTA = water withdrawal to water availability of each basins

WU = the water use is water withdrawal for different user group (Pfister *et al*., 2009), this example WU is water use from HAII

WA = the hydrological availability in each basins which calculated from total precipitation in basin, it called effective rainfall.

Therefore:

$$\mathrm{WTA} = \frac{9{,}361}{26{,}261}$$

$$= 0.36$$

2. WTA* Calculation

WTA* calculated from equation below

$$\mathrm{WTA}^{*} = \sqrt{\mathrm{VF}} \times \mathrm{WTA} \text{ for SRF}$$

$$\mathrm{WTA}^{*} = \mathrm{VF} \times \mathrm{WTA} \text{ for Nonï SRF}$$

Where:

WTA* = the weighted water withdrawalï toï availability (WTA*)

VF = the variation factor which this example use VFï SRF from method 3

Therefore:

$$\text{WTA*} = 2.18 \times 0.36$$

$$= 0.785$$

3. WSI calculation.

Calculated WSI from equation below

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

Threrfore:

$$\text{WSI} = \frac{1}{1+e^{-6.4(0.785)\left(\frac{1}{0.01}-1\right)}}$$

$$= 0.592$$

# Appendix C

Summation of data in four basins

**Appendix Table C1** Life cycle inventory of cassava root production for 1 ton of cassava starch

| **Input** | | | **Output** | | |
|---|---|---|---|---|---|
| **type** | **quantities** | **unit** | **type** | **quantities** | **unit** |
| **material** | | | **product** | | |
| stems | 1,412.082 | stems | cassava root | 4.092 | ton |
| cassava peel | 4.404 | kg | waste | 2,271.806 | kg |
| natural fertilizer (chicken manure) | 1.056 | ton | cassava stems | 3,569.087 | stem |
| nitrogen fertilizer | 5.112 | kg | **air pollution** | | |
| phosphorous fertilizer | 2.865 | kg | carbon dioxide | 34.033 | kg |
| potassium fertilizer | 5.468 | kg | nitrogen dioxide | 0.700 | kg |
| alacholor | 0.393 | kg | sulfur dioxide | 0.045 | kg |
| paraquat | 0.614 | kg | nitrous oxide | 0.180 | kg |
| glyphosate | 1.195 | kg | ammonium | 1.081 | kg |
| **fuel** | | | VOC | 0.237 | kg |
| diesel | 10.13 | kg | | | |

**Source: Keomary (2010)**

**Appendix Table C2** The secondary data of WSI calculation (Unit: $10^6$ $m^3$/year)

| | **Tha Chin** | **Mae Klong** | **Bang Pakong** | **Mun** |
|---|---|---|---|---|
| Area of watershed ($km^2$) | 13,681 | 30,837 | 7,978 | 69,701 |
| $WF_{pop}$ | 5,053 | 3,639 | 3,862 | 20,694 |
| $WF_{area}$ | 3531 | 7958 | 2059 | 17987 |
| Water needs | 8,075 | 9,361 | 2,998 | 13,428 |
| Runoff | 1,324 | 17,777 | 2,939 | 13,845 |
| $Rain_{eff}$ | 11,455 | 26,261 | 7,524 | 59,183 |
| Water in dams (The end of year) | 235 | 23,055 | 490 | 3,118 |
| Water in dams (yearly average) | 197 | 21383 | 426 | 2784 |

# CURRICULUM VITAE

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