CHAPTER 2

Literature Reviews

2.1 Water footprint (WF)

The water footprint (WF) was introduced by Hoekstra in 2002 (Chapagain and Hoekstra, 2004; Boulay *et al.*, 2013). At the first time, the term of WF was occurred in the water research report presented by UNESCO-IHE DELFT series No.11 (Hoekstra and Hung, 2002). The concept of WF referred as "virtual water". The "virtual water" concept was first given by Allen (1990s) as a solution to explain about how much water is consumed in one product or one processing. It could be called water embedded in a product, which included water in every process to produce some products, which could not be seen by naked eye (Hoekstra, 2003). Probably can said, this concept raised public the awareness for the global water issue and researching for the past decade (Boulay *et al.*, 2013).

2.1.1 Definition and concept of water footprint (WF)

The definitions of WF are shown on many researches which attempted to present for WF comprehensive as follows;

- A useful indicator to express the water uses for the production of commodities is the WF (Hoekstra, 2003).

- A tool that assess amount of freshwater consumption is the concept of the WF (Gerbens-Leenes and Hoekstra, 2008).

- The WF presents a wide perspective on how a consumer, producer, or product related to the consumption and pollution of freshwater system (Hoekstra *et al.*, 2009). The WF is an indicator of freshwater use that looks not only at direct water use of a consumer or producer, but also at the indirect water use (Hoekstra *et al.*, 2011).

Therefore, the WF can be revealed as the amount of precipitation and irrigation water that is used for producing a product, and also show amount of waste water that should be concerned about how to refine it before discharge into the environment system (Chapagain *et al.*, 2006). Moreover, the WF quantification not only volumes of water usage and pollution but also describes the locations in all of crops cultivation or related to the processing (Hoekstra *et al.*, 2009) or as the volume of fresh water usage that produces the product over the full supply-chain (Hoekstra *et al*., 2011). The WF can be considered concerning the opportunity of organizing a sustainable management.

The WF concept was similar to the concept of virtual water that has been shown in many publications. The 'virtual-water content' of the product aimed to express water embedded embodied or shadow water (Hoekstra and Chapagain, 2008). Virtual water refers to the water volume embodied in the product alone while the term 'water footprint (WF)' refers not only to the volume, but also to the sort of water that was used (green, blue, and grey WF) and identify when and where the water was used (Hoekstra *et al*., 2011). Moreover, calculation of water volume usage in factory as directly usage is easily to understand, while another water resource such as soil water is more complex to calculate (Lindholm, 2012). With the simplest properties, broader scope, related timing and location that water is used, Hoekstra *et al*. (2011) recommend to use water footprint. At the present, WF could visualize the hidden water usage behind products with the concept to provide more understanding the global character of fresh water. The WF comprehension will build up new fundamental policy for good management of the global freshwater resources (Hoekstra and Chapagain, 2008; Garrido *et al*., 2010; Hoekstra *et al*., 2011; Ercin and Hoekstra, 2012; Boulay *et al*., 2013; Kaenchan and Gheewala; 2013)

2.1.2 Component of water footprint (WF)

The WF is expressed in water volume per unit of mass (m^3/ton) or unit of time (m^3/year) that depends on different ultimately scope and goal. The total WF consists of 3 components (Figure 2.1) to reveal where the water embedded (Berger and Finkbeiner, 2010; Hoekstra *et al*., 2011; Boulay *et al*., 2013)

1) Green water footprint (WF)

This type of WF is referred to the rainwater that evaporated during crop growth. It is specific volume for rain water that crop only uses (not become run off).

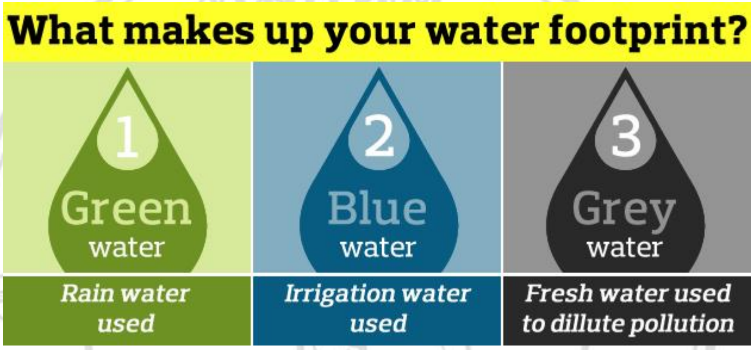

Figure 2.1 The total volume of the freshwater that is used during the production process (Source: http://www.raw.info/media/164327/raw_water_footprint.jpg)

2) Blue water footprint (WF)

This type of WF is referred to the surface and ground water in a catchment area that is consumed along the supply chain by processing (surface or groundwater). In Figure 2.2, obviously the processing can sometime conducted water such as reused water. This case was called 'non-consumptive water use' because it turns back to the resource. So it does not become to water footprint. In this case, if the most of water in irrigation always returns to the resource that can help to decrease the blue water footprint. As Cheesman (2004) said, a large variation in process water use - modern industry recycles its process water and reduces its process water use to almost zero.

3) Grey water footprint (WF)

If the water used for production included wastewater, it could be lower quality. Hence, the grey WF is the volume of water polluted as a volume of freshwater that required to dilute pollutants based on ambient water quality standards or improved before release to the nature that agreed by quality standards. Although, in reality, they cannot find pure water to dissolve, their concept needs to express the volume of water affected and amount of water that should be responsibility.

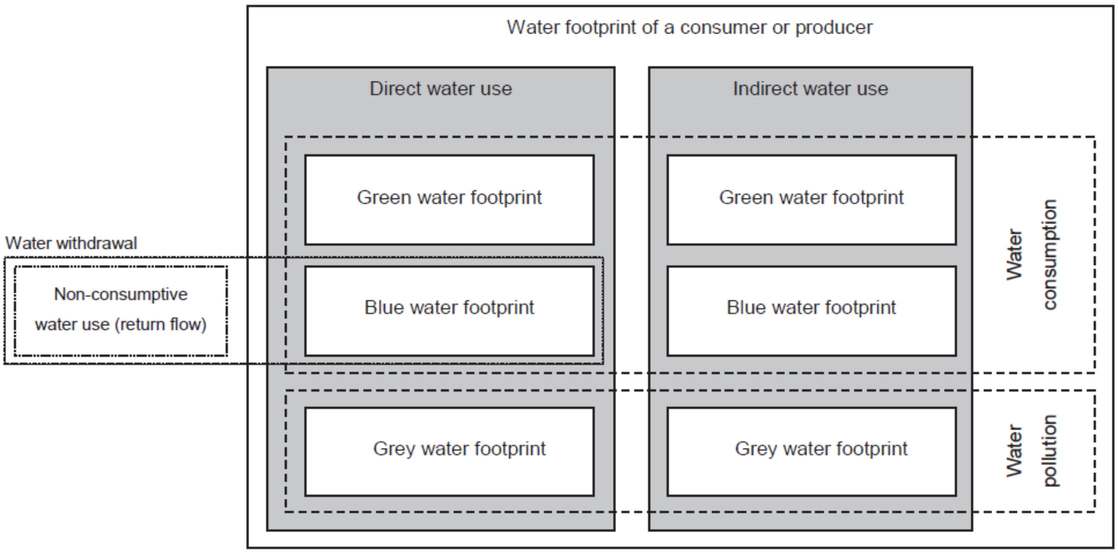

Figure 2.2 Diagram to show the relationship among 3 components that make the total water footprint (Hoekstra *et al*., 2011).

2.1.3 Overview of water footprint (WF) assessment for crop cultivation

According to the WF assessment manual of Hoekstra *et al*. (2011) the WF assessment should be conducted to follow the checklist (see in chapter 3) which contributes to set the goal and scope of the study. Then, the WF should be calculated and expressed as the water volume per unit of mass (m^3/ton) or unit of time (m^3/year). The main equation for calculation of the WF of crop cultivation is:

$$WF_{proc} = WF_{green} + WF_{blue} + WF_{grey} \quad \text{(volume/mass)} \qquad (1)$$

Where, WF_{proc} (m^3/ton) is the total WF of an agricultural production process.

Each component has to calculate before integration to become WF of processing or total WF of processing. For calculation of each component, there are many unique methods to reveal the value.

Kaenchan and Gheewala (2013) reviewed the overview for calculation of the water footprint from many studies in Thailand and other foreign countries. For easier understanding for practitioners, they concluded the calculation into for simple steps.

Equations 2 and 3 in Step 1 are showing the crop water use (CWU) both in green and blue water. The factor "10" is applied to convert the unit from mm into m^3/ha. And, "lgp" stands for the length of growing period in days. ET_c is measured through the growing period of crop from first day to the final day by CROPWAT 8.0 model. This model has been developed by the Food and Agriculture Organization of the United Nations (FAO) based on the FAO Penman-Monteith Method, because it is easy to measure and generally possible to use weather data that derived from several sources (the example results of CROPWAT 8.0 model in Table 2.1, 2.2 and 2.3) (Allen *et al.*, 1998).

The outcome of CROPWAT 8.0 is related to Step 1. It is crop water requirement (CWR) table that expresses both of green water evapotranspiration (ET_{green}) and blue water evapotranspiration (ET_{blue}). The WFA manual refers to green water evapotranspiration (ET_{green}) derived from the minimum of total crop evapotranspiration (ET_c) and effective rainfall (P_{eff}) as following equation (Hoekstra *et al*., 2011),

$$ET_{green} = \min (ET_c, P_{eff}) \text{ [length/time]} \quad (7)$$

For example, Holcomb (2010) investigated to quantify the four years WF of wheat and rice cultivation in the northwest part of Panjab State, India. The results showed the ET_{green} (mm/dec) of wheat in Northwest India was obtained using Equation 7 (Table 2.1).

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \quad (2)$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \quad (3)$$

Step 1*: The calculation by accumulation of daily crop evapotranspiration (ETc, mm/day)*

$$WF_{green} = \frac{\text{Green water use } (CWU_{green})}{Y} \quad (4)$$

$$WF_{blue} = \frac{\text{Blue water use } (CWU_{blue})}{Y} \quad (5)$$

Step 2: *The calculation of the green and blue water footprint for growing the crop (WF, m^3/ton)*

$$WF_{grey} = \frac{(\alpha \text{ x } AR) / (Cmax - Cnat)}{Y} \quad (6)$$

Step 3: *The grey water footprint (WF_{grey}, m^3/ton)*

$$WF_{proc} = WF_{green} + WF_{blue} + WF_{grey}$$

Step 4*: The total water footprint of the process of growing crops (WF_{proc}) is the sum of green, blue, and grey water footprints and its unit is m^3/ton (water volume per mass)*

Figure 2.3 The four steps for water footprint calculation reviewed by Kaenchan and Gheewala (2013)

For other example, Lindholm (2012) investigated to quantify the WF of oat cultivation in southwestern part of Finland. His results presented ET_{green} calculated by similar method that mentioned above. However, there is little differences from the study performed without irrigation in Finland for cereal production because the rainfall was sufficient for the crops. Therefore ET_{blue} (mm/dec) is not shown in Table 2.2.

Blue water use (irrigation water or blue water evapotranspiration) can be obtained by subtracting between the total crop evapotranspiration (ET_c) and effective rainfall (P_{eff}) as follows:

$$ET_{blue} = \max(0, ETc - Peff)\ [\text{length/time}] \qquad (8)$$

However if the effective rainfall is exceeded over crop evapotranspiration, the blue water evapotranspiration will be zero. This situation can be occurred under irrigation system because of sufficient rainfall (Hoekstra *et al.*, 2011). According to many studies, at some locations for agriculture precipitation is enough to cultivate a crop and therefore the WF can be revealed to be zero (Chapagain and Orr, 2009; Scholten, 2009; Deurer *et al.*, 2010; Holcomb, 2010; Ene *et al.*, 2012; Lindholm, 2012). For example, in Table 2.3 calculated by WFA Manual, it is described how to calculate ET_{blue} from CROPWAT 8.0 table. Particularly from April to the first decade of May, the ET_{blue} is zero because effective rainfall (P_{eff}) is larger than crop evapotranspiration (ET_c).

For Step 2 (Equation 4 and 5), after the crop water use, (CWU) both ET_{green} and ET_{blue} were calculated by CROPWAT 8.0. The green and blue water use (m^3/ha) will be completed (divided by the crop yield (Y, ton/ha)). The outcomes of calculation are the green and blue WF for growing the crop (WF, m^3/ton). By the way, the yields in all growing period (1 season) were accounted after harvesting. There are many scopes of cultivation area such as 1 km^3, district, province or whole nation.

Table 2.1 Total green-blue water evapotranspiration of wheat in Northwest India based on the CWR output table of CROPWAT 8.0.

Month	Decade	Stage	K_c	ET_c mm/day	ET_c mm/dec	P_{eff} mm/dec	Irr. Req. mm/dec	ET_{green} mm/dec	ET_{blue} mm/dec
Nov.	2	Initial	0.3	0.68	1.4	0.8	1.4	0.8	0.6
Nov.	3	Initial	0.3	0.61	6.1	5.1	1	5.1	1
Dec.	1	Initial	0.39	0.69	6.9	6.1	0.8	6.1	0.8
Dec.	2	Develop	0.71	1.08	10.8	7.1	3.7	7.1	3.7
Dec.	3	Develop	1.04	1.6	17.6	7	10.6	7	10.6
Jan.	1	Mid	1.12	1.75	17.5	6.3	11.2	6.3	11.2
Jan.	2	Mid	1.12	1.77	17.7	6	11.7	6	11.7
Jan.	3	Mid	1.12	2.02	22.2	8.1	14.1	8.1	14.1
Feb.	1	Mid	1.12	2.26	22.6	11.1	11.6	11.1	11.5
Feb.	2	Late	1.09	2.45	24.5	13.2	11.2	13.2	11.3
Feb.	3	Late	0.87	2.27	18.2	12.1	6.1	12.1	6.1
March	1	Late	0.61	1.82	18.8	10.7	7.5	10.7	8.1
March	2	Late	0.35	1.17	9.4	7.9	0	7.9	1.5
Total over entire growing period					193.7	101.5	90.9	101.5	92.2

(Source: Holcomb, 2010)

Table 2.2 The CWR table from CROPWAT 8.0 model results in ET_{green} served by the Jokioinen weather station to calculate for the growth period of oats in Finland.

Month	Decade	Stage	K_c	ET_c mm/day	ET_c mm/dec	P_{eff} mm/dec	Irr. Req. mm/dec	ET_{green} mm/dec
May.	2	Init	0.25	1.12	6.7	9	-	6.7
May.	3	Deve	0.27	1.3	14.3	16.8	-	14.3
Jun.	1	Deve	0.51	2.61	26.1	17.4	8.7	17.4
Jun.	2	Deve	0.78	4.26	42.6	18.6	24	18.6
Jun.	3	Deve	1.06	5.33	53.3	25.4	27.9	25.4
Jul.	1	Mid	1.23	5.64	56.4	37.3	19.1	37.3
Jul.	2	Mid	1.23	5.24	52.4	45.8	6.6	45.8
Jul.	3	Late	1.06	4.16	45.8	34.2	11.6	34.2
Aug.	1	Late	0.61	2.22	22.2	16	6.2	16
Aug.	2	Late	0.31	1.04	4.1	1.8	1.9	1.8
Total over entire growing period					323.8	222.2	106	217.5

(Source: Lindholm, 2012)

Table 2.3 Total green-blue water evapotranspiration based on the CWR output table of CROPWAT 8.0 in Appendix of WFA manual.

Month	Decade	Stage	Kc	ETc mm/day	ETc mm/dec	Peff mm/dec	Irr. Req. mm/dec	ETgreen mm/dec	ETblue mm/dec
Apr.	1	Ini	0.35	1.02	10.2	12.6	0	10.2	0
Apr.	2	Ini	0.35	1.13	11.3	13.8	0	11.3	0
Apr.	3	Ini	0.35	1.24	12.4	14	0	12.4	0
May	1	Ini	0.35	1.35	13.5	14.5	0	13.5	0
May	2	Ini	0.35	1.45	14.5	15	0	14.5	0
May	3	Dev	0.48	2.2	24.2	13.8	10.4	13.8	10.4
Jun.	1	Dev	0.71	3.55	35.5	12.7	22.7	12.7	22.8
Jun.	2	Dev	0.94	5.02	50.2	11.9	38.3	11.9	38.3
Jun.	3	Mid	1.15	6.6	66	9.8	56.3	9.8	56.2
Jul.	1	Mid	1.23	7.58	75.8	7.1	68.6	7.1	68.7
Jul.	2	Mid	1.23	8.05	80.5	5	75.6	5	75.5
Jul.	3	Mid	1.23	7.8	85.8	4.8	81	4.8	81
Aug.	1	Mid	1.23	7.59	75.9	4.1	71.8	4.1	71.8
Aug.	2	Lat	1.23	7.39	73.9	3.3	70.6	3.3	70.6
Aug.	3	Lat	1.13	6.05	66.6	5.7	60.9	5.7	60.9
Sep.	1	Lat	1	4.65	46.5	8.9	37.5	8.9	37.6
Sep.	2	Lat	0.87	3.51	35.1	11.2	23.8	11.2	23.9
Sep.	3	Lat	0.76	2.6	18.2	7.8	7	7.8	10.4
Over the total growing period					796	176	625	168	628

(Source: Hoekstra *et al.*, 2012)

For Step 3 (Equation 6), the calculation of the grey WF (WF_{grey}, m^3/ton) has difference methodology from green and blue WF. Many pollutants and fertilizers such as nitrogen, phosphorus and so on have been used to calculate the grey WF (WF_{gray}, m^3/ton). In this study, nitrogen is used. In Equation 6, C_{nat} is the natural concentration of pollutant in the receiving water body. In this study, it will be assumed to be zero (IFC, 2010; Hoekstra, 2011) because the receiving water is only precipitation. The Surface Water Quality Standards of Thailand recommended the maximum contaminant level or concentration (C_{max}) of nitrate nitrogen in surface water is 5.0 mg/L (PCD, 2013). 10% as a leaching rate was assumed to be a leaching run off fraction (α) of fertilizer application rate (AR, kg/ha) for all locations (Chapagain *et al*., 2006). This leaching rate was used by many researches (Chapagain *et al*., 2006; Hoekstra *et al*, 2009; IFC, 2010; Hoekstra *et al*., 2011; Kongboon and Sampattagul, 2012).

For the last step, (Equation 1), the total WF of the process of growing crops (WF_{proc}) is the sum of green, blue, and grey WF (m^3/ton).

By the way, the important factor that exists in Tables 2.1, 2.2 and 2.3 is K_c, which changes based on growing stage. K_c refers to the crop coefficient, which includes crop characteristics and averaged effects of evaporation from the soil. K_c is calculated by dividing the evapotranspiration efficiency of crop (ET_c) by the evapotranspiration of reference crop (ET_0) as follow:

$$K_c = ET_c/ET_0 \quad (9)$$

At the beginning of cultivation, K_c of crop is normally less than 1 and increase after the developing stage and decreases as late stage.

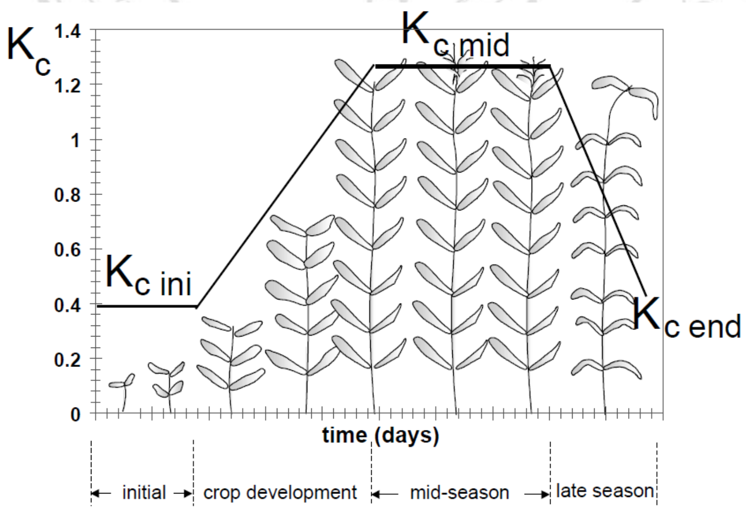

Figure 2.4 Generalized crop coefficient curve for the single crop coefficient approach (Allen *et al*., 1998)

Allen *et al.* (1998) showed K_c each stage of plantation in general crop in Figure 2.4. In this study, K_c from Royal Irrigation Department, Thailand (RID, 2010) was selected due to using as local characteristic data of Thailand while another study used K_c from the study of Allen and colleagues.

2.1.4 CROPWAT 8.0; tool for water footprint calculation

CROPWAT 8.0 is the computer program which was made by FAO (FAO, 2013). According to FAO (2013), CROPWAT is a decision support tool developed by the Land and Water Development Division of FAO. This model can provide the importance value for agriculture system. At the present, this model is available in the internet and free for download. In addition, the description for practitioner by FAO is given as follows (Cazanescu *et al*., 2009; FAO, 2013): "CROPWAT 8.0 for Windows is a computer program for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. In addition, the program allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying crop patterns. CROPWAT 8.0 can also be used to evaluate farmer's irrigation practices and to estimate crop performance under both rain-fed and irrigated conditions (FAO, 2013)".

Moreover, FAO (2013) refers to the documents from FAO, "Crop Evapotranspiration - Guidelines for computing crop water requirements" and "Yield response to water" which are No.56 and No.33 of FAO publication online. They are more educative for all the calculation procedures used in CROPWAT 8.0.

They cover necessary data such as standard crop and soil data, and it is possible to carry out without local data if it is not available. Likewise, if local climatic data are not available, these can be obtained from over 5,000 stations worldwide through CLIMWAT, the associated climatic database. It is very easy to conduct the database, but the data may be rather rough.

CROPWAT 8.0 includes documents of updated and new features as outcomes: for example,

- Climatic data inputted monthly, every 10 days and daily for calculation of reference evapotranspiration (ET_0)
- To allow use of data from CLIMWAT database

- Interactive user adjustable irrigation schedules
- Daily soil water balance output tables
- Graphical presentations of input data, crop water requirements and irrigation schedules
- Easy import/export of data and graphics through clipboard or ASCII text files
- Extensive printing routines, supporting all windows-based printers
- Multilingual interface and help system: English, Spanish, French and Russian

In addition, 3 items below should be needed for calculation of the WF assessment by CROPWAT 8.0.

1) Crop water requirement (CWR)

Crop water requirement is the water usage during growing period under local climate at that area. CWR is calculated as the product of crop efficiency (K_c) and reference crop evapotranspiration (ET0).

$$CWR = K_c \times ET_0 \quad (10)$$

Where, K_c is crop efficiency in which difference values depend on each stage over growing period (Allen *et al*, 1988). K_c each important growing stage, i.e. initial stage, middle stage and last stage, has to key in CROPWAT model. The different kind of irrigation system such as sprinkler irrigation and drip-irrigation affects directly on K_c. This study will select K_c from native organization in Thailand (Royal Irrigation Department of Thailand) to make clear the difference from another study and to assume that this value is suitable as a representative values particularly in Thailand. According to Equation 10, the crop water requirements (CWR) are fully assumed, and therefore the actual crop evapotranspiration (ET_c) will be equal to the crop water requirement (ET_c = CWR) (Allen *et al*., 1998; Hoekstra and Hung, 2002; Hoekstra, 2003; Hoekstra *et al*., 2011).

2) Effective rainfall (P_{eff})

Effective rainfall (P_{eff}) is practical rainfall used by soil and plant, and does not mean all of rainfall because of runoff and percolation (Dastane, 1978). Actually, there are various formulas to express P_{eff} based on the total rainfall. Moreover it also exists in CROPWAT model. The popular calculation for P_{eff} estimation is the method of the Soil Conservation Service of the United States Department of Agriculture (USDA SCS) that is widely used (Smith, 1998). Moreover many researches were reviewed, and USDA SCS formula is used for their studies (Chapagain and Orr, 2009; Hess, 2010; Holcomb, 2010; Lindholm, 2012). Thus, USDA SCS Method will be selected for this study.

3) Irrigation requirement to irrigate a crop

The irrigation requirement (IR) is calculated as the difference between crop water requirement and effective precipitation. The irrigation requirement is zero if the effective rainfall is larger than the crop water requirement. That is, IR = max (0, CWR – P_{eff}) as mentioned above in Equation 8. It is assumed that the irrigation requirements are fully met (Hoekstra and Hung, 2002; Hoekstra, 2003; Hoekstra *et al*., 2011).

2.1.5 The trend of water footprint (WF) study circles

Nowadays, many researchers attempt to present how to calculate green and blue WF by the WF assessment manual book such as Water Footprint Network (WFN). Moreover, Ridoutt and Pfister (2010) who presented Life cycle assessment (LCA) described about the inappropriate points when practitioners try to perform.

The public letter was revealed by Ridoutt *et al*. (2012) who has more publications about WF (for example, “A revised approach to water foot printing to make transparent the impacts of consumption and production on global freshwater scarcity”) were published by Ridoutt and Pfister (2010). That letter expresses the impossible to compare each product by WFA in three points. First point is about the land in our globe that has different physical factors. One of their reasons is that some countries have large dry areas. If WF was estimated, the WF should become large especially in irrigation system because there have not enough rainfall. Ridoutt and Pfister illustrated the example that WF of animal product was larger than the WF of crop products. If the comparison was carried out by WFA, it could not be corrected. And, they gave the arguments on this because livestock conducted on non-arable land without irrigation system. It is different factor. However, both have similar important products for global food production and WF can make for easier decision. Second point, they suggested the estimation should be firstly begun at droughty area, because there is large water footprint that means a lot of water resource’s effects. The last point, due to most of his works, he focused on the appropriate method to approach WF. Therefore, Ridoutt and his colleague presented to redefine the WF through the developing method such as LCA that based on water pressure of study area.

Hoektra *et al*. (2012) as WF creators reply immediately to the letter in the same journal. There are three points to reply to the arguments of Ridoutt and his colleagues. Firstly, the concept of WF assessment is to quantify volumes of water that consume along supply chain. Moreover, WFA still reveals the portions of water for wise allocation. Although there are different factors in our globe, the size of WF still shows availability of water at that place and time. Therefore, this is important and primary role play of WFA. Secondly, WF assessment should actually be performed in droughty area. However, it does not mean the absence of estimation in rich water area. The WF concept is very important in exposed true water that is meaningful for wise allocation. Therefore, for both the areas, it is important to know the WF. Otherwise, the big problem will happen if the rich water area is out of considering. Lastly, some principles of Ridoutt and his colleagues discord with WFA aspects and the new principle redefined by them does not make sense in WFA perspective.

Nevertheless, this argument still exists in water footprint circles. Many points presented the weakness and inappropriate of WF assessment of Hoekstra's method by Ridoutt and his colleagues' publication. However, they still conducted their method to adjust WFA by LCA. They described their method more accurately and the most simply to use with LCA and water stress characterization factors. Moreover, it is obviously that the argument of WFA by Hoektra and colleague cannot declare potential risk in environment at the present (Ridoutt and Pfister, 2010).

At the same time, WF assessment by Hoekstra and his colleagues is still popular and many studies followed their method (Scholten, 2009; Holcomb, 2010; Seewiseng *et al*., 2012; Ene *et al*., 2012; Jarernsook *et al*., 2012; Kongboon and Sampattagul, 2012; Lindholm, 2012; Sun *et al*., 2012; Yoo *et al*., 2013; etc.). A lot of researches indicated the convenience to perform. Herath *et al*. (2013) discussed the difference between WF assessment and LCA. As the result, both methods have differences in WF assessment. For WF assessment, Herath and his colleague agree with the argument of Ridoutt and his colleague. This focus is an unclear comparison between products by WFA. However, the results for LCA of Ridoutt and his colleague also should be more educated on the issue. In particular, in term of green WF, Ridoutt and his colleague neglect through their works while Hoekstra and colleague described about usefulness of this term and recommend keeping it. Moreover, LCA is hardly followed by new practitioners.

Basically, different methods contribute to difference values especially by calculation. But each method was attempted to prove water shortage problem. It seemed to be problem in how to choose the best methodology. But now, the suggestions to combine both methods were proposed by Boulay *et al*. (2013). They concerned both concepts, and focused on the advantage only to develop those methods together (Figure 2.5).

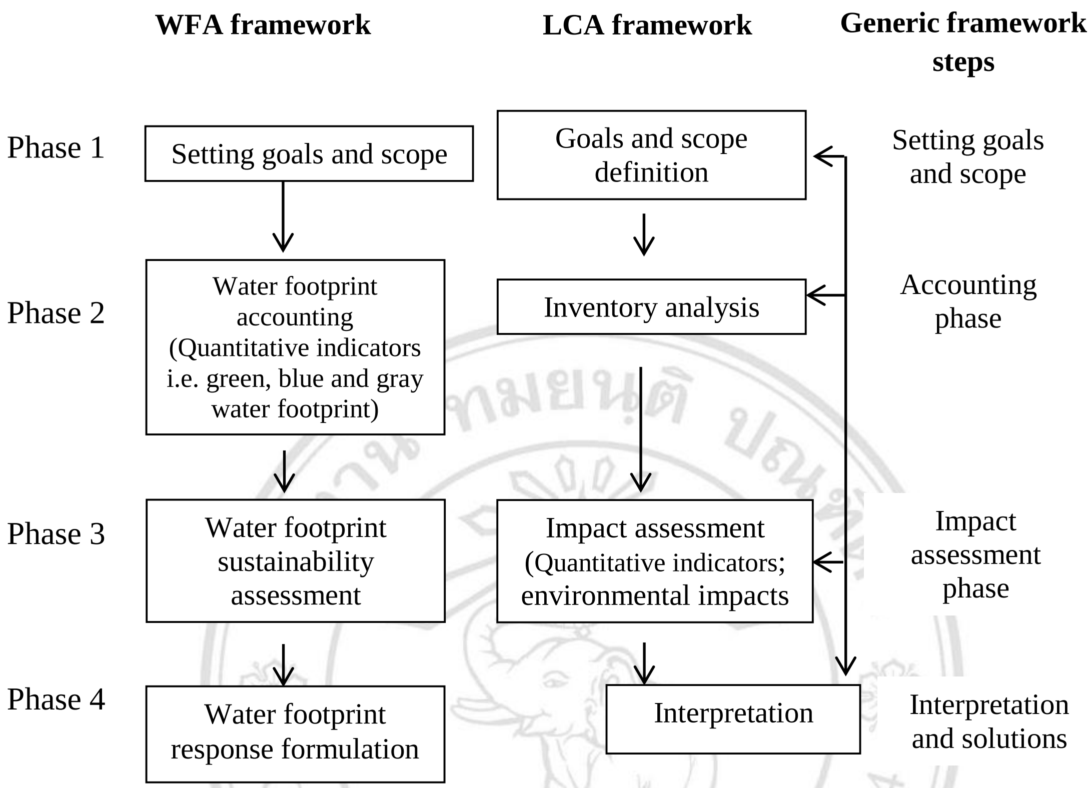

Figure 2.5 Comparison of LCA and WFA, illustrating the large similarity and the difference in quantitative indicators (Source: Boulay *et al*., 2013)

To select different tools contributes different results. The trend to select local characteristic data for WF assessment such as climatic data, property of plant and soil of each location was considered. The transparency of WF that behind each product should be used unique data that more appropriate to exposure water footprint (Chapagain and Orr, 2009; Ridoutt *et al*., 2010).

Moreover, for almost all WF studies in Thailand WFA also was selected to calculate green and blue WF as shown in Table 2.4.

Therefore, this study will be followed by these methodologies for WF assessment because of easy comparison with the result to other studies.

WF was used as a tool to express amount of water that consumed in many products and processing such as;

- The WF of poultry, pork and beef (Gerbens-Leenes *et al*., 2013),
- The WF of coffee and tea (Chapagain and Hoekstra, 2007),
- The WF of paddy rice (Yoo *et al*., 2013) and
- The WF of sugarcane and cassava (Kongboon and Sampattagul, 2012)

For calculation of them, it was necessary to use climatic database from local meteorological station each area or from CLIMWAT 2.0 modeling programs by FAO (FAO, 2012). The climatic data is necessary to conduct as the appropriate format that required by the CROPWAT 8.0 model (Scholten, 2009; Holcomb, 2010; Hoekstra *et al*. 2011; FAO. 2013; Jeswani and Azapagic, 2011). Although the climate data can be calculated by CLIMWAT 2.0 modeling programs, it is better to use climatic data from local meteorological institute on that area. Due to local character of cultivation's water usage, the evapotranspiration data will be required. Therefore, the WF assessment should be carried out using climate data from the nearest and the representative meteorological station located near the crop field (Chapagain and Orr, 2009; Ridoutt *et al*., 2010; Hoekstra *et al*., 2011; Kongboon and Sampattagul, 2012; FAO, 2013).

Table 2.4 The water footprint studies in Thailand among 2011-2013

No.	Title of research	Kind of target	Location	Author	Years
1	Water Footprint of Bioethanol Production from Cassava in Thailand	Bioethanol Production from Cassava	Thailand	Chinatippakorn and Thamrongrat	2011
2	Water footprint of Maize in Nakhonsawan Province	Maize	Nakhonsawan	Sukumalchart *et al*.	2011
3	the water footprint of sugarcane and cassava in northern Thailand	sugarcane and cassava	northern Thailand	Kongboon and Sampattagul	2012

Table 2.4 The water footprint studies in Thailand among 2011-2013 (Cont.)

No.	Title of research	Kind of target	Location	Author	Years
4	Water Footprint of Bioethanol Production from Sugarcane in Thailand	Bioethanol Production from Sugarcane	Thailand	Kongboon and Sampattagul	2012
5	Water footprint of rice in the left bank of the Chainat Pasak canal area on Khok Katiam Operation and Maintenance Project, Lopburi Province	rice	Lopburi	Thammaniyom *et al*.	2012
6	The water footprint of oil palm crop at the Chaipattana-Mae Fah Luang Reforestation Project, Phetchaburi Province	oil palm	Phetchaburi	Seewiseng *et al*.	2012
7	A review of the Water Footprint of Biofuel Crop Production in Thailand	Biofuel Crop Production	Thailand	Kaenchan and Gheewala	2013
8	Water Footprint Assessment of Ethanol Production from Molasses in Kanchanaburi and Supanburi Province of Thailand	Ethanol Production	Kanchanaburi and Supanburi Province	Chooyok *et al*.	2013

The climate and rainfall data from local meteorological station will make WF more clearly and accurately, also provide the good representative WF of that area. In addition, the local character of a product's water usage as raw data can give more clear and accurate WF value, as well as contributes better understanding of real situation (Chapagain and Orr, 2009; Ridoutt *et al.*, 2010).

All in all, the WF assessment manual proposed by Hoekstra *et al*. (2011) is mostly use illustration as reference methodology for WF assessment in this study. It presents a principal and methodology about "how to assess the WF?". Moreover, they introduce CROPWAT model of Food and Agriculture Organization of the United Nations (FAO) to calculate green and blue evaporation as initial necessary data toward green and blue WF. This model is the simplest, but not the most accurate option to measure crop water use either.

2.1.6 Case study

1) Water footprint (WF) in abroad

Sun *et al.* (2013) assessed WF of major crop in Hetao irrigation district, China (i.e. spring wheat, maize and sunflower), it revealed of variability of influent factor. The results show the average total WF was 3.91m^3/kg, and the ratios of blue and green WF were 90.91 % and 9.09 %, respectively (grey WF is zero). These results obviously show most of WF were occupied by blue WF.

Holcomb (2010) investigated to quantify WF of wheat and rice cultivation for four years in the northwest part of Panjab state, India. This study applied WF Manual that provides several checklists to design the study. For WF calculation, the crop water use of green and blue WF was calculated by CROPWAT 8.0 model. In this model, the climate and rainfall data which obtained CLIMATE 2.0 model are used for calculation. For grey WF data calculation, nutrient management was performed in rice and wheat cropping system and nitrogen was used as the critical pollutant (Khurana *et al*., 2008). The crop area, production and averaged yields of rice and wheat were investigated between agriculture years 2005-2006 and 2008-2009. The average total WF of wheat was 776 m^3/ton, in which green WF was 234 m^3/ton, blue WF is 212 m^3/ton and grey WF was 330 m^3/ton. The average total WF of rice was 1,606 m^3/ton in which green WF was 425 m^3/ton, blue WF was 801 m^3/ton and grey WF was 380 m^3/ton. The WF data of both plants cultivation were useful as the tool for helping minimizing ground water usage. Moreover, green WF as rainwater harvesting and grey water reuse heightened awareness. Likewise, they will continue to push this issue to the front of both government and independent research agendas.

Lindholm (2012) investigated to quantify the WF of oat cultivation in southwestern part of Finland. WF manual was used to provide several checklists and to design the study. For WF calculation, blue WF was based on direct water consumption. The crop water use of green WF was calculated by CROPWAT model. The climate and rainfall data were obtained from the Finnish Meteorological Institute. Data for grey WF calculation was referred to the study of phosphorus as a nutrient in watershed by Salmi and Kipinä-Salokannel (2010) and used phosphorus as the critical pollutant because this study wanted to ensure a good representative of critical pollutant. As the result, estimation of blue WF resulted in little value because lacking of raw data from factories. The average green WF of oat fields in Finland was 510 m^3/ton (494 and 527 m^3/ton). The grey WF was 3,996 m^3/ton. If nitrogen was used as the critical pollutant for calculation of grey WF, the value would increase because nitrogen seemed to require more water for dilution than phosphorus. However, it was difficult to discuss about the outcomes with external stakeholders who do not have an insight in water management concept.

Jefferies *et al.* (2012) assessed WF of tea in Kenya, Indonesia and India and margarine in Germany. The WF was calculated using the methodology described by Hoekstra *et al.* (2011). The average WF of a carton of 50 g tea was 294 L for green water, 10 L for blue water. While a 500 g tub of margarine was 553 L for green water, 109 L for blue water. In this case, grey water was neglected in both studies. Moreover, they applied LCA method to quantify WF, and the results showed that grey water of tea was 13 L and margarine 114 L (Normally, LCA method shows only blue WF and neglects green WF because the rainfall does not have investment).

2) Water footprint (WF) in Thailand

In the past, WF of Thailand presented by foreign researcher and for WF estimation, the climate data from FAO were selected. For the local characterizations of water usage for cultivation (such as evapotranspiration), the climatic data and rainfall from local meteorological station were required. By using these data, WF should be more clearly and accurately, and will be good representation of WF each country (Chapagain and Orr, 2009; Ridoutt *et al*., 2010; Hoekstra *et al*., 2011).

Kongboon and Sampattagul (2012) assessed the WF of sugarcane and cassava in northern part of Thailand in four periods between 2008 and 2010. The crop water use of green WF was calculated by CROPWAT model, it use the climate and rainfall data obtained from Thai Meteorological Department. The data for grey WF calculation was referred to nutrient management performance in sugarcane and cassava cropping system by Department of agriculture of Thailand (DOA, 2010) and nitrogen was used as the critical pollutant. As the result, average WF of sugarcane, 202 m^3/ton, was less than WF of cassava, 509 m^3/ton. Moreover, the results were compared to each province of northern part of

Thailand. And the differences were caused by various factors, e.g. climate, crop characteristics and cropping system. The conclusion of this study was expected to prepare suitable guideline for good management of water resource and increase of crop yield.

Chooyok *et al.* (2013) investigated WF of bio-ethanol produced from molasses Kanchanaburi and Supanburi Province. The green, blue and grey WF were calculated by WFA of Hoekstra *et al*. (2011). As the results, the green, blue and grey WF in Kanchanaburi Province were 848.7 m^3/ton, 209.6 m^3/ton and 45 m^3/ton, respectively. While the green, blue and grey WF in Supanburi Province were 708.3 m^3/ton, 102.9 m^3/ton, and 64.8 m^3/ton, respectively. The results depend on variability of many factors such as spatial factor, soil and the plantation date which are related to make different size of WF.

2.2 Cadmium

Cd is an odorless, silver-white, blue-tinged lustrous heavy metal. Chemical forms of Cd are usually oxide, chloride, or sulfide. Cadmium (Cd) is found in mineral form called greenockite, which is commonly found in association with zinc ore (ATSDR 2011; NTP, 2011).

2.2.1 Cadmium contamination in soil

Cadmium (Cd) contamination occurs naturally in the environment as some inorganic forms which resulted from volcanic emissions and weathering of rocks. In addition, anthropogenic sources have increased the background levels of Cd in soil, water and living organisms (EFSA, 2009). Normal level of Cd in surface soils ranges from 0.01 to 2.7 mg/kg. However, in contaminated area, the high value of 1,781 mg/kg was measured (Kabata-Pendias, 2001). The average Cd content of the Earth’s crust is given as 0.1 mg/kg (Kabata-Pendias, 2011). In Thailand, it is mentioned in the soil quality standards for habitat and agriculture that maximum level of Cd should not exceeded 37 mg/kg (PCD, 2013). While in the European Union (EU) Maximum Permissible (MP) level is 3.0 mg Cd/kg for agricultural (sludge amended) soils (EEC, 1986).

The main source of Cd in the air is the burning of fossil fuels such as coal and oil and the incineration of municipal wastes. While the mining and smelting affect increasing Cd in soil (Alloway and Steinnes 1999; Brumbaugh *et al*., 2005; Hasselbach *et al*. 2005). Moreover, the use of fertilizer such as phosphate can be a major source of Cd input to agricultural soils (EPA 1985). The concentrations of Cd in surface depends on several factors such as mobility and natural geochemistry, fertilizers and atmospheric deposition. Cd in soil is affected by several factors such as pH of the soil and the availability of organic matter. In particular, Cd in soil tends to be more absorbed when the soil pH is low (acidic condition) (Elinder, 1992; USEPA, 1999; ATSDR, 2012). Cd usually binds strongly to organic matter and remain immobilize form in soil (Autier and White, 2004). In the polluted area, Cd is accumulated in plants and organisms. Moreover, along with the increase of Cd concentration in soil, Cd in food and feed will increase. Therefore, Cd is harmful for environment (ATSDR, 2012)

2.2.2 Absorption and toxicity of cadmium in organism

1) Inhalation exposure

Cd in humans through inhalation exposures mainly affects the lung, i.e. pulmonary irritation. Especially, the worker who lives in high contamination area of Cd will have severe damage of the lungs, and may result in death by difficulty in breathing. On the other hand, in lower level of Cd, persons who work for long periods accumulate Cd in their kidney it may result in kidney disease if Cd is sufficiently in high concentration. Moreover, animals also have lung and nasal cavity damages problem cause by Cd (USEPA, 1999; ATSDR, 2012).

2) Oral exposure

Food and water that contaminated with Cd may cause health problems. High level of Cd severely irritates the stomach, leads to vomiting and diarrhea, and sometimes to death. However, even if level of Cd is lower, to take Cd for long periods may lead to accumulation of Cd in the kidney. If the accumulation of Cd is high, the kidney will get damage. In case of bone problem, the exposure to lower level of Cd for a long time may also cause fragile and easily broken bone. Animals may have damages of kidney, bone, anemia, liver, nerve or brain by uptake of Cd through eating. Additionally, according to some studies, lung cancer has been found in workers and rats that exposed to Cd in the air.

Many organizations make clear that the cancer problem in human body caused by Cd. For example, the U.S. Department of Health and Human Services (DHHS) has concluded that Cd compounds are human carcinogens. The International Agency for Research on Cancer (IARC) has concluded that Cd is carcinogenic to humans. For the EPA concluded that Cd is a probable human carcinogen. These organizations give caution to people in regulations and recommendations that Cd can be expressed as “not-to-exceed” levels (USEPA, 1999; ATSDR, 2012).

2.2.3 Cadmium accumulation in the study sites, Mae Sot District, Tak Province, Thailand

In 2003, Department of Agriculture, Ministry of Agriculture published serious information about soil and rice Cd contamination in Mae Sot District. The report concluded that the level of rice Cd contamination should be given awareness and immediate attention to prevent Cd poisoning among the risky population. In 2004, the US Food and Drug Administration also reported that the rice was contaminated with Cd in Mae Sot District, Tak Province (Simmons *et al.*, 2005).

Simmons *et al.* (2005) investigated to measure Cd contamination in rice and soil at Phatat Pha Daeng and Mae Tao Mai sub-districts, Mae Sot, Tak Province. As the results, the land was classified as Cd contamination area. The measurement results of rice grains collected from 1,067 fields showed that the Cd concentration range was less than 0.01 to 7.75 mg/kg. It was 38.75 times of the recommended maximum level (ML) of 0.2 mg /kg for Cd in rice grain in Thailand (CAC, 2002). The measurement results of soil samples collected from 1,090 fields reported that the Cd concentration range was from 0.1 to 284 mg/kg. The data exceeded the European Union (EU) Maximum Permissible (MP) level of 3.0 mg/kg in agricultural soils. These results show that the area is in a serious condition for rice farming (EEC, 1986; Simmons *et al.*, 2005).

Because of Cd contamination in rice, the Thai government prohibited rice cultivation and introduced cultivation of other non-edible crops. There was an attempt to change to other crops in 2006 by establishing the Mae Sot Clean Energy Company, the company which produces bio-ethanol from sugarcane in Cd contaminated area. The company recommended the farmers to cultivate sugarcane, and bring it for ethanol production. According to Sereno *et al*. (2007), sugarcane was a potential plant for the phytoremediation of Cd contaminated soil (451 mg/kg gives no symptoms). On the other hand, Sritumpawa (2007) investigated the uptake of Cd by sugarcane from the contaminated soil in Mae Sot, and performed pot experiment. Cd absorbed by sugarcane in the field was higher than the level obtained by the pot experiment. Moreover, roots of sugarcane were the best part of absorption of Cd (high Cd concentration, 28 mg/kg).

For the purposes of phytoremediation and bio-ethanol production, sugarcane was planted by the support of the bio-ethanol company at the Cd contaminated areas of over 40,000 Rai. This study aims to assess Cd accumulation by sugarcane root in the Cd contaminated areas.

2.3 Sugarcane (*Saccharum officinarum* L.)

Sugarcane is classified to the class Monocotyledones, order Glumaceeae, family Gramineae, group Andropogoneae and genus Saccharum. The sugarcane has 3 main parts i.e. the stalk, leaf, and root. The growth rate of sugarcane is shown in Figure 2.6. The growth begins slowly in the germinating bud as initial stage and grows gradually until the maximum growth. The growth of sugarcane is affected by complex internal and external factors. Normally, external factors like moisture, temperature, light, soil condition and nutrition are more important affecting growth (Miller *et al.*, 2014).

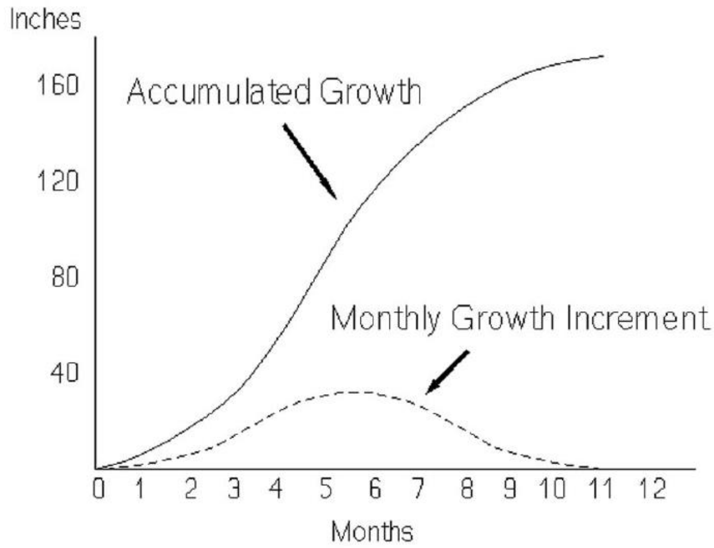

Figure 2.6 Hypothetical growth curve for Florida sugarcane (Miller *et al.*, 2014)

Sugarcane has 4 phases of growth as shown in Figure 2.7 (NETAFIM, 2014) i.e.

1) Germination phase is the initial stage until the completion of germination of buds or the primary shoot above surface (0-30 days).

2) Tillering phase starts from around 40 days after planting and may last up to 120 days. It is the appropriate number of stalks required for good yield. Therefore, it is special treated period for farmer

3) Stalk elongation phase or grand growth phase starts from 120 days after planting and lasts up to 270 days in 12-months cycle. In this phase, stalks grow rapidly with almost 4-5 internodes per month under favorable conditions.

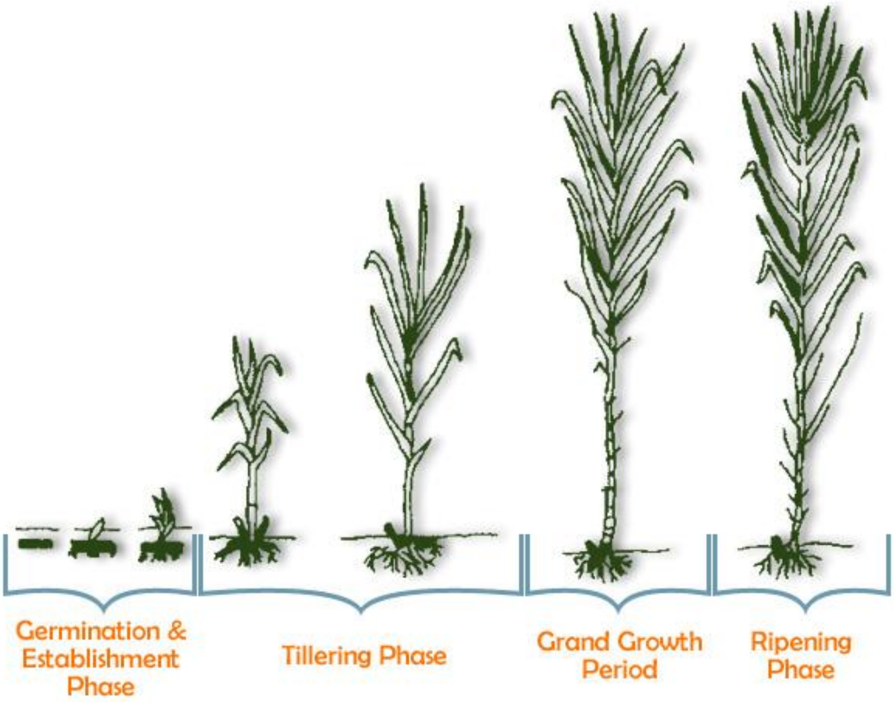

Figure 2.7 Crop growth phases

(http://www.sugarcanecrops.com/sites/sugarcanes/_media/mediabank/187_mb_file_5b914.jpg)

4) Maturation and ripening phase in a 12-months cycle lasts for about three months (270-360 days). Sugar synthesis and rapid accumulation of sugar takes place during this phase, and the vegetative growth is reduced as shown in Figure 2.6.

FAO (2014) reported sugarcane is useful plant for sugar and biofuel. Thailand is the fourth country in the world which produces sugar next to Brazil, India and China. According to the top production of sugarcane in 2012, the production of Thailand of sugarcane was about 96,500,000 ton/year, and the yield per hectare was about 56.4 ton.

Some regions in Thailand have adequate amount of precipitation, and sugarcane can grow without irrigation system.

For WF study, during the past decades, bio-ethanol production from sugarcane has become to be competitive with sugar production. Therefore, sugarcane is popular to estimate amount of water usage for management decision (Scholten, 2009; Gerbens-Leenes and Hoekstra, 2012).