CHAPTER 2

THEORY

2.1 Life cycle assessment (LCA) methodology

The following is an introductory overview of Life Cycle Assessment (LCA) by the U.S. Environmental Protection Agency (EPA) which states that life cycle assessment is a "cradle-to-grave" approach to assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in conventional analyses (e.g., raw material extraction, material transportation, ultimate product disposal). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection.

The term "life cycle" refers to the major activities in the course of a product's lifespan from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required for manufacturing the product. Figure 2.1 illustrates the possible life cycle stages that can be examined in an LCA and the typical inputs/outputs measured.

Specifically, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases
- Evaluating the potential environmental impacts associated with identified inputs and releases
- Interpreting the results to help decision-makers make a more informed decision.

The LCA process is a systematic, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in Figure 2.2:

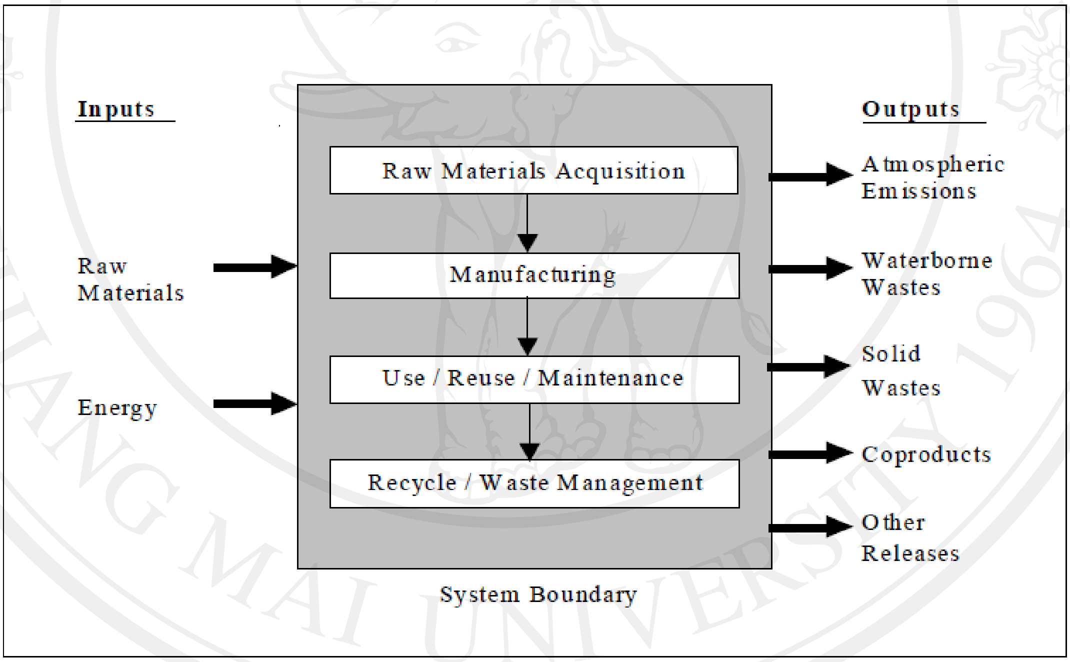

Figure 2.1 Life Cycle Stages.

(EPA, 2006).

Goal Definition and Scoping: Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.

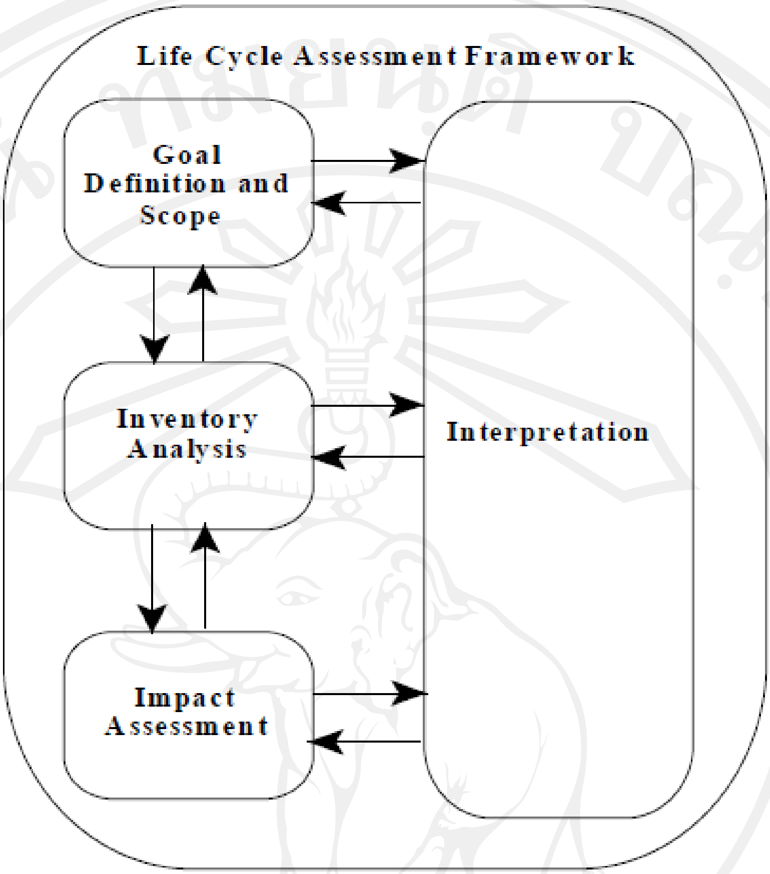

Figure 2.2 Phases of LCA.
(EPA, 2006).

Inventory Analysis - Identify and quantify energy, water and material usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).

Impact Assessment - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

Interpretation - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

Life cycle assessment is unique because it encompasses all processes and environmental releases beginning with the extraction of raw materials and the production of energy used to create the product through the use and final disposition of the product. When deciding between two or more alternatives, LCA can help decision-makers compare all major environmental impacts caused by products, processes, or services.

2.2 Carbon footprint methodology

Iribarren, D., et al. (2010) was defined that the carbon footprint (CF) involves the estimate of the overall amount of greenhouse gas (GHG) emissions associated with a product (i.e., any goods or services) along its supply chain, including the use, end-of-life recovery and disposal. Causes of these emissions were, for instance, electricity production in power plants, heating with fossil fuels, transport operations and other industrial and agricultural processes (EPLCA, 2007). According to Carbon Trust et al. (2008), the term 'product carbon footprint' referred to the GHG emissions of a product across its life cycle, from raw materials through production (or service provision), distribution, consumer use and disposal/recycling. It included the greenhouse gases, i.e., carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), together with families of gases including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)''.

Contrary to the popular belief, CF is not a new topic since it is related to the quantification of life cycle impact indicators for the global warming midpoint category. In fact, CF opponents understood this tool just as a sub-set of the data covered by a more complete Life Cycle Assessment (LCA).

LCA was an internationally standardized technique (ISO, 2006a, b) useful for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. However, the use of carbon footprints for communication purposes questioned the aptitude of the existing ISO standards to consistently and comprehensively address the environmental impacts due to GHG emissions from products (SETAC, 2008). Therefore, despite the existence of undeniable links between LCA and CF, the emergent methodological framework for the latter makes CF more than a mere LCA restricted to the global warming impact category.

Standardization efforts were necessary to provide guidance for people interested in quantifying the carbon footprint of a product. Within this framework, several initiatives originated to meet the increasing market demand for climate relevant information along supply chains. These initiatives arose mainly from prestigious institutions, such as the International Organization for Standardization (ISO), the UNEP/SETAC Life Cycle Initiative, the British Standards Institution (BSI), the World Business Council for Sustainable Development (WBCSD) together with the World Resources Institute (WRI), the Japanese Ministry of Economy, Trade and Industry (METI), and the French Environment and Energy Management Agency (ADEME). Behind this stream of proposals was the involvement of high profile retailers such as Tesco, Marks & Spencer and Carrefour, which were interested in implementing a CF scheme for their products. With the aim of defining a common standard for the assessment of GHG emissions associated with products (goods and services), the BSI, the Carbon Trust and the Department for Environment, Food and Rural Affairs (Defra) started in 2007 a procedure that gave birth to the Publicly Available Specification 2050:2008, together with other complementary documents such as the Guide to PAS 2050 (Iribarren, D., et al., 2010).

In Thailand, the national guideline on product carbon footprint (2013) was established by the national technical committee on product carbon footprint under a collaborative project of Thailand Greenhouse Gas Management Organization (Public Company) or "TGO", National Metal and Materials Technology Centre (MTEC), and National Science and Technology Development Agency (NSTDA).

The guideline specifies requirements for the assessment of the life cycle of GHG emissions of goods and services based on key life cycle techniques and principles. Thus, the guideline builds on the LCA guidance and requirements articulated in ISO 14025:2006, ISO 14040:2006 and ISO 14044:2006, adopting a life cycle approach to emission assessment and the functional unit as the basis of reporting. Furthermore, this specification also deals with other relevant methods and approaches in the field of GHG assessment, such as ISO 14064-1:2006, Japanese

Technical Specification “General principles for the assessment and labeling of Carbon Footprint of products” and PAS 2050:2008.

The life cycle approach in LCA covers the following procedures: raw material acquisition, manufacture, use and final waste disposal including related transport in all stages. This guideline can be used for assessing the full carbon footprint (i.e., cradle-to-grave covering all life cycle stages mentioned above) or partial carbon footprint (i.e., cradle-to-gate covering only raw material acquisition and manufacture).

The guide to PAS 2050:2011: How to carbon footprint your product, identify hotspots and reduce emissions in your supply chain, a work by the British Standards Institution (BSI, 2011), presented an approach to carbon footprint assessment which in turn could be decomposed into a series of steps. The steps were sequential and could not be carried out in isolation. The calculations of carbon footprint, as shown in Figure 2.3, consist of four steps, i.e., scoping, data collection, calculation and interpretation, which are similar to the phases of LCA.

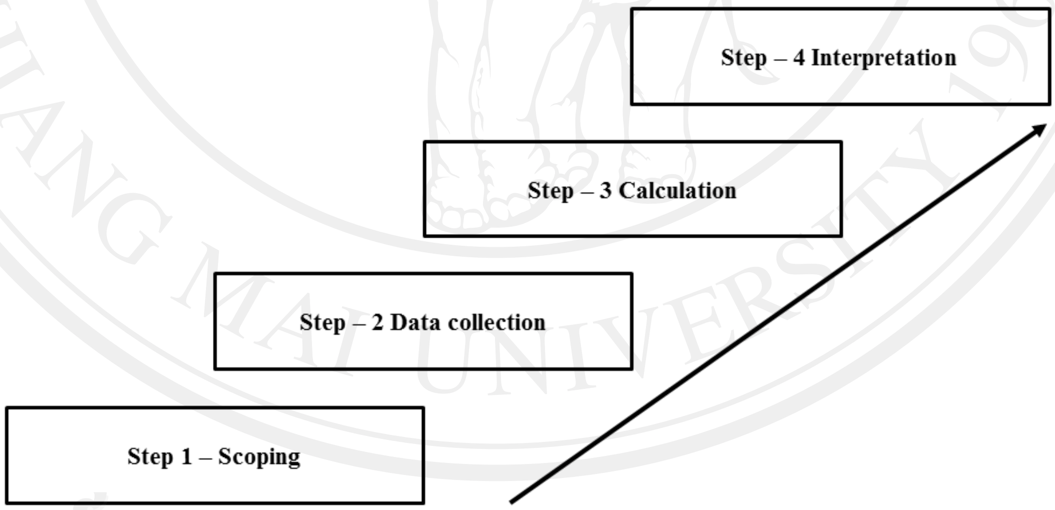

Figure 2.3 Steps of carbon footprint calculation.

2.2.1 Scoping

Scoping is the most important step when undertaking a product carbon footprint study. It ensures that the right amount of effort is spent in getting the right data from the right places to achieve robust results in the most efficient manner possible. There are four main stages to scoping, and they are best undertaken sequentially.

i) Describe the product to be assessed and the functional unit of analysis

It is vital that the product to be assessed be clearly defined at the outset. For its carbon footprint, the product must be defined in terms of a 'functional unit'. The functional unit (FU) defines the function of the product that will be assessed and the quantity of product to which all of the data collected will relate.

ii) Draw a map of the product life cycle

Once the functional unit has been defined, the next step is to map out the life cycle of the product to be assessed. The process-mapping stage is an initial brainstorm exercise to map all of the 'flows' of materials and energy in and out of the product system as they are used to make and distribute the product. This sets the framework for the 'system boundary' which considers these 'flows' in more detail.

iii) Setting the 'system boundary' of the study

Consider the following when setting system boundaries, i.e., which GHG emissions and removals to include, cradle-to-gate versus cradle-to-grave assessments, which processes and activities to include or exclude and time boundaries.

The GHG emissions include carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), plus a wide range of halogenated hydrocarbons including CFCs, HCFCs and HFCs. Each of these types of GHG molecule is capable of storing and re-radiating a different amount of energy, thereby making different contributions to global warming. The relative 'strength' of a GHG compared with CO_2 is known as its global warming potential (GWP), as shown in Table 2.1. Carbon footprints are assessed within a 100-year time boundary.

Table 2.1 Global warming potential at 100-year time horizon

Greenhouse gas	Chemical formula	GWP
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Hydroflurocarbons and hydrochlorofluorocarbons	HFCs and HCFCs	77-14,800
Perfluorocarbons	PFCs	7,390-17,700
Sulphur hexafluoride	SF_6	22,800

Source: IPCC (2006)

The system boundary of this study allows two standard types which are often used for different purposes as shown in Figure 2.4: Cradle-to-gate or Business to Business (B2B) which takes into account all life cycle stages from raw material extraction up to the point at which the product leaves the organization undertaking the assessment; and cradle-to-grave or Business to Consumer (B2C) which takes into account all life cycle stages from raw material extraction right up to disposal at the end of life.

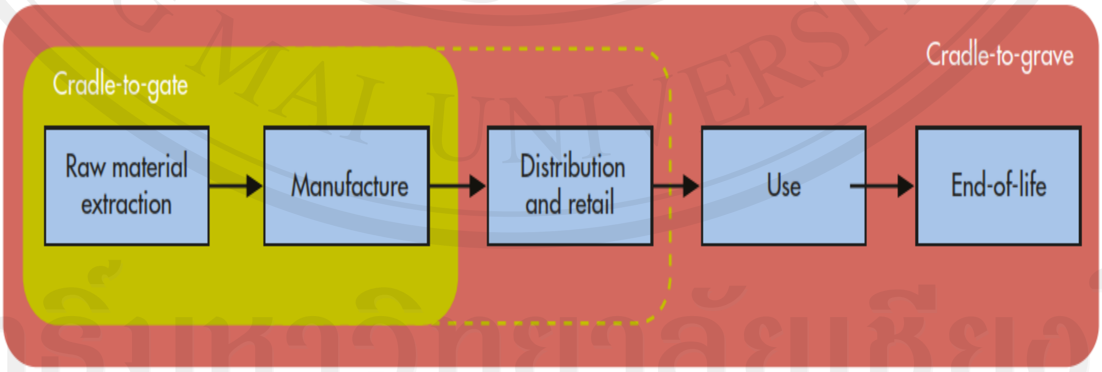

Figure 2.4 Cradle-to-gate and cradle-to-grave assessments.
(BSI, 2011)

iv) Prioritize data collection activities

Having defined a system boundary, the next step in the scoping stage is to prioritize data collection activities. Data collection is commonly the most time- and resource-intensive step in any carbon footprint assessment; therefore, prioritizing the data that are needed is advisable. It is usually not worth spending significant time and effort getting precise and accurate data for a life cycle stage that have very little impact on the overall footprint. Efforts and priorities should also be linked to the intended purpose of the study.

2.2.2 Data collection

The data needed to carry out a product carbon footprint calculation fall into the following categories: activity data and emission factors. Activity data refers to quantities of inputs and outputs (materials, energy, gaseous emissions, solid/liquid wastes, co-products, etc.) for a process, typically described for a unit of production for a specified year of production. This also includes details of any transportation of incoming materials, wastes or distribution of the final product (distances travelled, vehicles used, etc.).

Activity data can be from either primary sources, i.e., first-hand information specific to the activity in question, collected internally or from the supply chain; or secondary sources, i.e., average or typical information about a general activity from a published study.

Emission factors are values that convert activity data quantities into GHG emissions, based on the 'embodied' emissions associated with producing materials/fuels/energy, operating transport carriers, treating wastes, etc. These are usually expressed in units of kg CO_2e and are most often from secondary sources.

i) Draw up a data collection

Having prioritized data needs during scoping, it is good practice to develop a data collection plan to focus efforts and provide a reference to draw on. The data collection plan should outline top targets for primary data collection and highlight areas where secondary data will be sought instead, recognizing where primary data collection may not be feasible. The data collection plan does not have to be too detailed, or formal, but should cover all of the data needed for the carbon footprint assessment.

ii) Engaging suppliers in primary data collection

Engaging suppliers in the carbon footprint process will be helpful to collect specific primary data for the supply chain, giving greater insight into emissions sources. The action can also encourage future co-operation in terms of finding practicable opportunities to reduce the footprint.

iii) Collecting and using secondary data

Secondary data are typically used in footprinting studies as a source of emission factors which convert primary activity data (material/energy/process inputs and outputs) into GHG emissions (in $kgCO_2e$), of information to fill gaps in primary activity data, and of information to calculate the impact of 'downstream' life cycle stages, e.g., use and end-of-life.

iv) Collecting data for 'downstream' activities

Downstream activities refer to processes that occur during product distribution, retail, use and end-of-life. Typically one needs to collect only primary activity data for distribution unless retail is part of the business activities. However, the use phase can be the most important life cycle stage for products that need energy for operation, require cooking, etc.

v) Assessing and recoding data quality

The accuracy or 'quality' of the product carbon footprint result is ultimately dependent upon the quality of the data used to calculate it. It is critical that one consider the quality of the primary and secondary data used and demonstrate that the data appropriately represent the footprinted product.

2.2.3 Calculation

The useful first step in the calculation process is to map all of the flows occurring and calculate the quantities associated with each flow. Having developed a process map, it can be used to map out all of the inputs, outputs, distances and other useful activity data for each process stage.

Activity data are often collected in many different formats and presented in different units (e.g., inputs and outputs for a ton of raw material produced, or a year's worth of production, or a hectare's worth of production). The important next step is to balance the flows shown in the process map so that all inputs and outputs reflect the provision of the functional unit/reference flow as defined in Step 1. This can be either performed within the process map itself or in an Excel spreadsheet or other software tools. The carbon footprints were estimated from the activity data (kg/litres/kWh/tkm, etc.) multiplied by the emission factor (kgC_2Oe per kg/litre/kWh/tkm, etc.). These are summed to obtain a total carbon footprint against each life cycle stage and for the total system.

2.2.4 Interpretation

The output from footprint calculations will be a total footprint value for the agreed functional unit. This will be broken down according to the contributions of each material, process and life cycle stage. Carbon footprinting can be a basis for reducing carbon emissions and energy use and also for conveying a positive message to different stakeholders. Through the interpretation of the carbon footprint of the product, it should be evident which areas of the life cycle, which materials and which processes should be targeted for reduction. Focus reduction initiatives on those processes identified by the assessment as being of most concern. The nature of these reduction initiatives will largely be specific to the product being assessed and the production processes involved. The potential influence of design changes can also be assessed using product carbon footprinting. By manipulating carbon footprint models to change material inputs, processing requirements or use phase configurations, different design intervention options can be investigated and compared against the original product life cycle. It is also possible to go further and develop simple tools that allow designers to use what-if scenarios and determine the impact on total GHG emissions when changing a particular material or process.

2.3 Water footprint methodology

The water footprint (WF) concept was primarily rooted in the desire to illustrate the hidden links between human consumption and water use and between global trade and water resources management (A. Ertug Ercin and Arjen Y. Hoekstra, 2012). The

WF was developed as an analogy to the ecological footprint concept and was first introduced by Hoekstra in 2002 (Hoekstra, 2003) to provide a consumption-based indicator of water use. The WF is an indicator of freshwater use that shows direct and indirect water use of a producer or consumer.

The WF started to gain broad interest from around 2008, the year in which the Water Footprint Network (WFN) was established. The WFN is a network of academic institutions, governments, non-govern-mental organizations, companies, investors and UN institutions. One of the aims of the WFN is to ensure the establishment of one common language and a coherent and scientifically sound framework for Water Footprint Assessment (WFA) that serves different interests.

In 2009, about seven years after the first use of the WF concept, the WFN published the first version of the global standard for WFA. Two years later, the second version was published (Hoekstra et al., 2011). This standard, which was produced in a process of consultations with organizations and researchers worldwide and subjected to scientific peer review, has comprehensive definitions and methods for WF accounting. It shows how WFs are calculated for individual processes and products, as well as for consumers, nations and businesses. It also includes methods for WF sustainability assessment and a list of WF response options. As anticipated, the definitions and methods have been challenged, but no alternative methodological framework has been developed. The WFN standard contains definitions of the WF, of process steps, products, producers and consumers, as well as of the WF within a geographically delineated area.

The WF is an indicator of freshwater appropriation, measured in terms of water volumes consumed (evaporated or incorporated into a product) and polluted per unit of time. The WF concept is further defined more specifically for a particular process or product, and for any well-defined group of consumers (e.g. individual, family, village, city, province, state, and nation) or producers (e.g. public organization, private enterprise, and economic sector). From a producer's or consumer's perspective, the WF is an indicator of both their direct and indirect water use. The WF is a geographically and temporally explicit indicator, showing not only volumes of water use and pollution, but also their locations.

2.3.1 Components of a water footprint

Figure 2.5 show components of a water footprint which consist of:

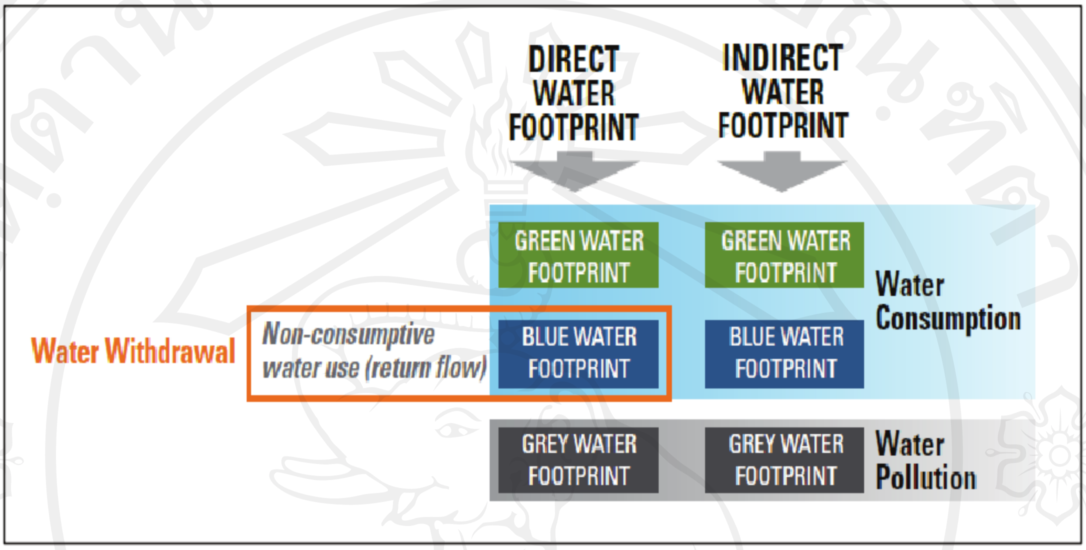

Figure 2.5 Components of a water footprint.

(Source: Hastings, E. and Pegram, G. 2012)

i) Direct and indirect water use

The direct water footprint of a consumer or producer (or a group of consumers or producers) refers to the freshwater consumption and pollution that is associated with the water use by the consumer or producer, for example, the water used in manufacturing a sugar product. The direct WF is distinct from the indirect water footprint, the latter of which refers to the freshwater consumption and pollution 'behind' the products being consumed or produced. The indirect WF is equal to the sum of the water footprints of all products consumed by the consumer or of all (non-water) inputs used by the producer, for example, the water required to grow the sugarcane used in manufacturing the sugar product. Typically, these indirect water requirements were far greater than the direct water requirements (Elizabeth Hastings and Guy Pegram, 2012).

ii) Consumptive versus non-consumptive water use

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

iii) Blue, green and grey water

A water footprint is divided into blue, green and grey water consumptions.

- ❖ A green water footprint refers to the volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (i.e., products based on crops or wood), in which the green WF refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood.

- ❖ A blue water footprint refers to volume of surface water and groundwater consumed for the production of goods or provision of services. Consumption refers to the volume of freshwater used and then evaporated or incorporated into a product. It also includes water abstracted from surface or groundwater in a catchment and returned to another catchment or the sea. It is the amount of water abstracted from groundwater or surface water that does not return to the catchment from which it was withdrawn.

- ❖ A grey water footprint is an indicator of freshwater pollution that can be associated with the production of a product over its entire supply chain. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards. It is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above the agreed-upon water quality standards.

'Water footprint of a product' or virtual-water content refers to the amount of freshwater that is used directly or indirectly to produce the product or service. It is estimated by considering water consumption and pollution in all steps of product chain as shown in Figure 2.6. The accounting procedure is similar to all sort of products, be it products derived from the agricultural, industrial or service sector

while virtual-water content refer to volume alone. In general, the actual volume of water footprint was higher than the amount of water embedded in goods. In addition, majority of water was used in the life cycle of the crop as Figure 2.5 (Hoekstra et al., 2011).

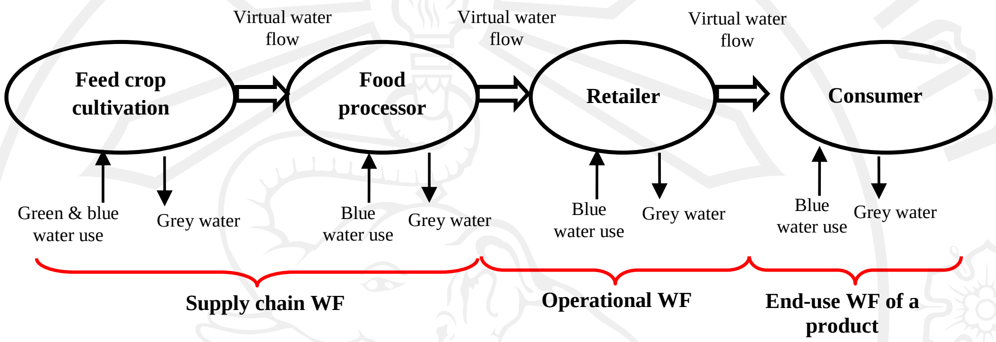

Figure 2.6 Chain supply in the production process of water footprint. (Source: Hoekstra et al., 2011)

The WF is a multi-dimensional indicator showing volumes of water consumption by source and polluted volumes by type of pollutant. A unit of WF is presented in terms of water volume per unit of product or time, while the WF of a process is shown as water volume per unit of time when divided over the quantity of products from the process. A product WF is always expressed in m^3/ton or liter/kg. However, the factors that influence the WF of a product are crop type, agricultural product system, climatic condition and location.

That is a volumetric measure of water consumption and pollution. It is not a measure of violence of the local environmental impact of water consumption and pollution. The water footprint offered a better and wider overview on how a consumer or producer connected to the use of freshwater systems.

2.3.2 Steps in water footprint assessment

Water footprint assessment is an analytical tool that is instrumental in helping to understand how activities and products relate to water scarcity and pollution and the related impacts; and what can be done to ensure that activities and products do not contribute to unsustainable use of freshwater. As a tool, the water footprint assessment provides insight; however, it does not tell the users 'what to do'. Rather, it helps them to understand what can be done. A full water footprint assessment based on the water footprint assessment manual consists of four steps as shown in Figure 2.7.

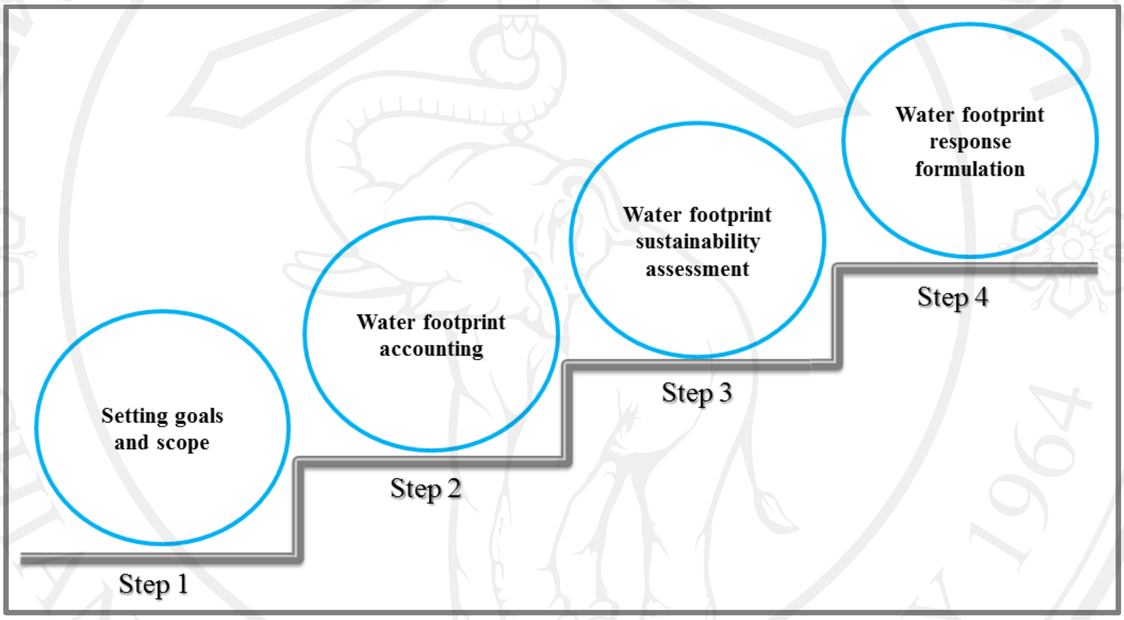

Figure 2.7 Steps in the water footprint assessment.

The first step is setting the goals and scope of the assessment in order to determine how to approach and structure the analysis. The second step is that of water footprint accounting, which entails performing the calculations for a particular process, producer or consumer in a specified geographical area. The third step is a sustainability assessment, which seeks to understand the environmental, social and economic sustainability of the water footprint which has been calculated. Finally, the fourth step of formulating response strategies is aimed at making the water footprint more sustainable (Hastings, E. and Pegram, G. 2012). In the goals and scope setting, one could decide to focus only on accounting or cease after the sustainability assessment step, leaving the discussion about response for later. Besides, in practice, this model of four subsequent steps was more a guideline than a strict directive. Returning to earlier steps and iteration of phases might be necessary (Hoekstra et al., 2011).

2.3.2.1 Step 1 – Setting goals and scope

It is important to first clarify the goal of a water footprint assessment, as the approach and methodology will change depending on the goal and context. The entity around which a water footprint will be completed will be determined by the goal of the study. If a water footprint is aimed at understanding supply chain risks for a business, a footprint around a particular product or business will be most helpful. Common entities around which water footprints are conducted include:

- ❖ Process steps
- ❖ Products
- ❖ Consumer or group of consumers
- ❖ Geographically delineated area, e.g., national, municipality, province or other administrative unit, catchment area or river basin.
- ❖ Business or business sector
- ❖ Humanity as a whole

Once the entity has been identified, additional questions regarding the scope and focus of the assessment must be answered, including:

❖ Blue, green and/or grey water: Whether to include blue, green and grey water in the study, or whether to focus on only one or two components. Blue water is usually scarcer and has high opportunity costs than green water, and thus is typically the focus of analysis and of traditional water resource tools. However, green water may be of interest because it often plays a significant role in agricultural production and has not been included in traditional types of analysis. Grey water will be interesting when water pollution is a concern.

❖ Truncation of supply chain: Where to truncate the analysis when looking at the supply chain. The general rule expressed in the Water Footprint Assessment Manual is to include all water use in the supply chain that 'significantly' contributes to the footprint although exact guidelines have not been developed. The water footprint of labor in the supply chain, including the food, clothing, and other consumption of workers in the process, is generally excluded in a water footprint. This is because it would result in a never-ending analysis and double-counting.

❖ Period of time: Water availability and demand vary within a year and from year to year. The water footprint will also vary depending on the chosen time period. For example, a blue water footprint will be higher in a dry year than a year with significant rainfall. Thus, an assessment must specify whether it is looking at a particular year, a number of years, or an average.

❖ Production or consumption: A water footprint can be conducted from a consumption perspective, a production perspective, or both. Some of the above entities around which footprints are completed are clearly either consumption or production-focused. For example, a footprint for a product will focus on the freshwater required throughout the supply chain for the production of that product. A footprint for a consumer will determine the freshwater required for the products consumed according to that consumer's habits. However, for a geographically delineated area such as a country, either production or consumption water footprint may be of interest and should be clarified for the assessment.

❖ Internal or external: Distinguishing between internal and external water footprints is most relevant when discussing the footprint of a geographically delineated area, such as a country. An internal water footprint refers to the domestic freshwater used to produce the goods and services consumed by the population of a particular country or area, whereas an external water footprint refers to the freshwater used in other countries to produce goods and services which are then imported and consumed by the country of interest. This concept becomes important because an external water footprint implies reliance on foreign countries to meet freshwater needs, and thus is relevant to discussions on using trade to address water scarcity and also discussions on food and water security.

2.3.2.2 Step 2 – Water footprint accounting

Water footprint accounting is the step of calculating the water footprint. As indicated above, a water footprint could be calculated for many different entities (Hastings, E. and Pegram, G. 2012). The discussion below provides the methodology for this study, including the blue, green and grey water footprints of crops and products. The water footprint assessment provided more detailed methodology and additional examples (Hoekstra, 2011).

i) Water footprint of a crop

Many products contain ingredients from agriculture or forestry. Crops are used for food, feed, fiber, fuel, oils, soaps, cosmetics and so on. Since the agricultural sector is a major water-consuming sector, products that involve agriculture in their production system will often have a significant water footprint. For all of those products, it is relevant to particularly look into the water footprint of the process of growing the crops. This section discusses the details of assessing the process water footprint of growing crops. The method is applicable to both annual and perennial crops, where trees can be considered a perennial crop. The total water footprint of the process of growing crops (WF_C) is the sum of the green, blue and grey water footprints as given in the following equation:

$$WF_C = WF_{C,green} + WF_{C,blue} + WF_{C,grey} \tag{2.1}$$

The water footprint of a crop is expressed as water volume per unit of mass. Usually, we express the unit in m^3/ton, which is equivalent to liter/kg.

<u>Green and blue water footprints</u>

The green and blue water footprints of a crop are calculated in a similar way as given in the following equations:

$$WF_{C,green} = \frac{CWU_{green}}{Y} = \frac{10 \times \sum_{d=1}^{lgp} ET_{green}}{Y} \tag{2.2}$$

$$WF_{C,blue} = \frac{CWU_{blue}}{Y} = \frac{10 \times \sum_{d=1}^{lgp} ET_{blue}}{Y} \tag{2.3}$$

The green component in the water footprint of a crop ($WF_{C,\ green}$, m^3/ton) is calculated as the green component in crop water use (CWU_{green}, m^3/ha) divided by the crop yield (Y, ton/ha). The blue component ($WF_{C,\ blue}$, m^3/ton) is calculated in a similar way.

The green and blue components in crop water use (CWU, m^3/ha) are calculated by accumulation of daily evapotranspiration (ET, mm/day) over the complete growing period, where ET_{green} represents green water evapotranspiration and ET_{blue} blue water evapotranspiration. The factor 10 is meant to convert water depths in millimeters into water volumes per land surface in m^3/ha. The summation is done over the period from the day of planting (day 1) to the day of harvest (lgp or length of growing period in days).

- **Evapotranspiration**

Evapotranspiration (ET) is the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration (FAO 1998). Evapotranspiration can be calculated following either the procedure in the Irrigation and Drainage Paper No.56, 'Crop Evapotranspiration', which has been published by the Food and Agriculture Organization of the United Nations (FAO) or 'Crop Water Requirement and Irrigation scheduling' by Andreas P. SAVVA and Karen FRENKEN.

The main factors affecting evapotranspiration are climatic parameters, crop characteristics, management practices and environmental aspects. The main climatic factors affecting evapotranspiration are solar radiation, air temperature, air humidity and wind speed. The crop type, variety and development stages also affect evapotranspiration. Differences in crop resistance to transpiration, crop height, crop roughness, reflection, canopy cover and crop rooting characteristics result in different evapotranspiration levels in different types of crops under identical environmental conditions. Factors such as soil salinity, poor land fertility, limited use of fertilizers and chemicals, lack of pest and disease control, poor soil management and limited water availability at the root zone may limit the crop development and reduce evapotranspiration. Other factors that affect evapotranspiration are groundcover and plant density. Cultivation practices and the type of irrigation system used can alter the microclimate, affect the crop characteristics, or affect the wetting of the soil and crop surface. All these affect evapotranspiration. As illustrated in Figure 2.8, there exist three conditions of evapotranspiration: the reference crop evapotranspiration (ET_o), the crop evapotranspiration under standard conditions (ET_c), and the crop evapotranspiration under non-standard conditions ($ET_{c\ adj}$).

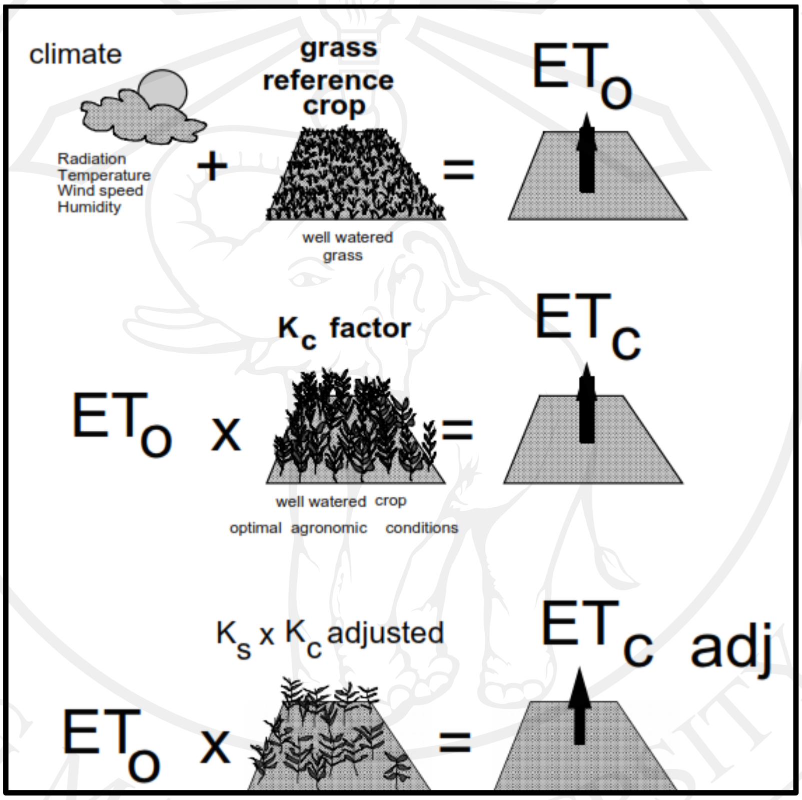

Figure 2.8 Reference crop evapotranspiration (ET_o), crop evapotranspiration under standard conditions (ET_c) and non-standard conditions ($ET_{c\ adj}$)

(Source: Richard G. Allen et al., 1998)

- **Reference crop evapotranspiration**

The evapotranspiration from a reference surface not short of water is called the reference crop evapotranspiration and is denoted by ET_o. The reference surface is a hypothetical grass reference crop with specific characteristics. The concept of ET_o was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development stage, and management practices. As water is abundant at the evapotranspiring surface, soil factors do not affect evapotranspiration. Relating evapotranspiration to a specific surface provides a reference to which evapotranspiration from other surfaces can be related. It removes the need to define a separate evapotranspiration level for each crop and stage of growth.

The only factor affecting ET_o is climatic parameters. As a result, ET is a climatic parameter and can be computed from weather data. ET_o expresses the evaporative demand of the atmosphere at a specific location and time of the year, and does not consider crop and soil factors.

ET_o can be computed from the meteorological data by the FAO Penman-Monteith method, requiring solar radiation, air temperature, air humidity and wind speed data in the computation, is given in the following equation:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \quad (2.4)$$

where
ET_o reference evapotranspiration [mm day^{-1}]
R_n net solar radiation at the crop surface [MJ m^{-2} day^{-1}]
G soil heat flux density [MJ m^{-2} day^{-1}]
T mean daily air temperature at 2 m height [°C]
u_2 wind speed at 2 m height [m s^{-1}]
e_s saturation vapor pressure [kPa]
e_a actual vapor pressure [kPa],
e_s-e_a saturation vapor pressure deficit [kPa]
Δ slope vapor pressure curve [kPa °C]
γ psychrometric constant [kPa $°C^{-1}$]

- **Crop evapotranspiration under standard conditions**

The crop evapotranspiration under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields under optimum soil water conditions and achieving full production under the given climatic conditions. The values of ET_c and CWR (Crop Water

Requirements) are identical, whereby ET refers to the amount of water lost through evapotranspiration and CWR the amount of water needed to compensate for the loss.

ET_c can be calculated from climatic data by directly integrating the effect of crop characteristics into ET_0. Using recognized methods, ET_0 is estimated. Experimentally determined ratios of ET_c / ET_0, called crop coefficients (K_c), are used to relate ET_c to ET_0 as given in the following equation:

$$ET_c = ET_0 \times K_c \tag{2.5}$$

Where ET_c = Crop evapotranspiration (mm/day)

ET_0 = Reference crop evapotranspiration (mm/day)

K_c = Crop coefficient

Crop coefficients (K_c) are properties of plants used in predicting evapotranspiration (ET). K_c is a dimensionless number. The FAO's K_c curve is comprised of four straight line segments representing the initial period, the development period, the midseason period, and the late season period, as shown in Fig. 2.9. K_c varies according to plant growth stages, i.e., (K_c)ini: crop coefficient for initial growth stage; (K_c)dev: coefficient for plant development stage; (K_c)mid: coefficient for mid-season; and (K_c)end: coefficient toward the end of the season.

- **Crop evapotranspiration under non-standard conditions**

The crop evapotraspiration under non-standard conditions, $ET_{c\ adj}$, is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions. When cultivating crops in the field, the real crop evapotranspiration may be different from ET_c due to non-optimal conditions, such as occurrence of pests and diseases, soil salinity, poor soil fertility, and waterlogging. $ET_{c\ adj}$ is calculated using a water stress coefficient (K_s) and/or by adjusting K_c for all kinds of other stresses and environmental constraints on crop evapotranspiration as given in Equation 2.6. The calculation procedures for $ET_{c\ adj}$ will not be covered in this module. For more details on this concept the reader is referred to the FAO (1998).

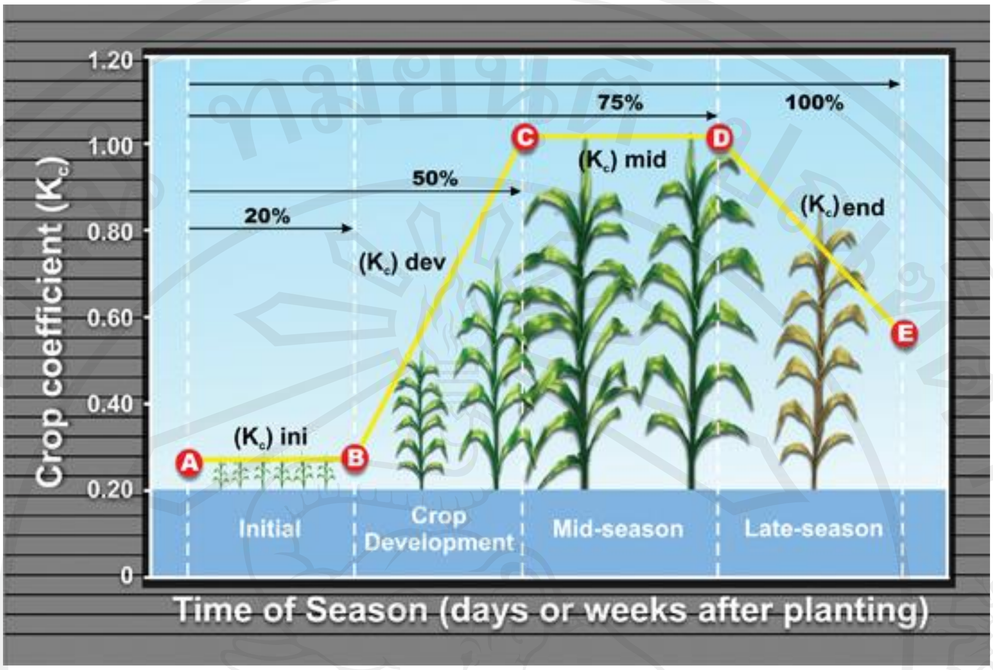

Figure 2.9 Crop coefficients and crop development stages

(Source: NebGuide, 2013)

$$ET_c = K_s \times K_c \times ET_0 \quad (2.6)$$

Evapotranspiration from a field can be either measured or estimated by means of a model based on empirical formulas. Nevertheless, measuring the evapotranspiration is costly and unusual. Generally, one estimates evapotranspiration indirectly by means of a model that uses data on climate, soil properties and crop characteristics as inputs. Besides, there are many alternative ways to model ET and crop growth. One of the models frequently used was the EPIC model (Williams et al, 1989; Williams, 1995), also available in grid-based form (Liu et al, 2007). Another model was the CROPWAT model developed by the Food and Agriculture Organization of the United Nations (FAO, 2010a), which was based on the method described in Allen et al (1998). Yet, another model was the AQUACROP model, specifically developed for estimating crop growth and ET under water-deficit conditions (FAO, 2010b).

❖ Calculation of Green and blue evapotranspiration using the CROPWAT 8.0 model

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 for 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 farmers' irrigation practices and to estimate crop performance under both rainfed and irrigated conditions. All calculation procedures used in CROPWAT 8.0 were based on the two FAO publications of the Irrigation and Drainage Series, i.e. No. 56 "Crop Evapotranspiration - Guidelines for computing crop water requirements" and No. 33 titled "Yield response to water" (FAO, 2010b).

Green and blue water evapotranspiration during crop growth could be estimated with the CROPWAT model (FAO, 2010b). The model offered two different options to calculate evapotranspiration. The first option which was the simplest but not the most accurate option was the crop water requirement (CWR) option. This option estimated evapotranspiration under optimal condition, which meant that crop evapotranspiration (ET_c) equaled the crop water requirement (CWR). Being optimal meant disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions (Allen et al, 1998). The crop water requirement option could be run with climate and crop data alone. ET_c was estimated with a ten-day time step and over the total growing season using the effective rainfall. To calculate the effective rainfall, the method of the Soil Conservation Service of the United States Department of Agriculture (USDA SCS) was chosen as it is one of the most widely used methods. The model calculated ET_c as in the following equation 2.5.

The green water evapotranspiration (ET_{green}) was calculated as the minimum of total crop evapotranspiration (ET_c) and effective rainfall (P_{eff}) as given in the equation 2.7, with a time step of ten days. The total green water evapotranspiration was obtained by summing ET_{green} over the growing period. The blue water evapotranspiration (ET_{blue}) was estimated as the difference between the total crop evapotranspiration (ET_c) and the total effective rainfall (P_{eff}) on a ten-day basis as given in the equation 2.8. When the effective rainfall was greater than the crop total crop evapotranspiration, ET_{blue} was equal to zero. The total blue water evapotranspiration was obtained by adding ET_{blue} over the whole growing period.

$$ET_{green} = \min(ET_c, P_{eff}) \quad \text{[length/time]} \qquad (2.7)$$

$$ET_{blue} = \max(0, ET_c - P_{eff}) \quad \text{[length/time]} \qquad (2.8)$$

The second option was the irrigation schedule option (including the possibility to specify actual irrigation supply in time). It is recommended that the second option be applied whenever possible because it was applicable to both optimal (standard condition) and non-optimal (non-standard condition) growing conditions and because it was more accurate as the underlying model includes a dynamic soil water balance (Hoekstra et.al, 2011). The calculated evapotranspiration was called ET_a, the adjusted crop evapotranspiration. ET_a might be smaller than ET_c due to non-optimal conditions. The water movements in the soil, the water holding capacity of the soil, and the ability of the plants to use the water could be influenced by different factors, such as physical condition, fertility and biological status of the soil. ET_a was calculated using a water stress coefficient (K_s) as given in the following equation 2.6.

After running the model, the total water evapotranspired (ET_a) over the growing period was equal to what is called the 'actual water used by crop' in the model output. The blue water evapotranspired (ET_{blue}) was equal to the minimum of 'total net irrigation' and 'actual irrigation requirement' as specified in the model output. The green water evapotranspired (ET_{green}) was equal to the total water evapotranspired (ET_a) minus the blue water evapotranspired (ET_{blue}) as simulated in the irrigation scenario.

Grey water footprint

The grey component in the water footprint of growing a crop or tree ($WF_{C,grey}$, m^3/ton) was calculated as the chemical application rate to the field per hectare (AR, kg/ha) times the leaching-run-off fraction (α) divided by the maximum acceptable concentration (c_{max}, kg/m^3) minus the natural concentration for the pollutant considered (c_{nat}, kg/m^3) and then divided by the crop yield (Y, ton/ha) as given in the following equation:

$$WF_{C,grey} = \frac{(\propto \times AR)/\,(C_{max} - C_{nat})}{Y} \qquad (2.9)$$

The natural concentration in a receiving water body is the concentration in the water body that would occur if there were no human disturbances in the catchment. For human-made substances that naturally do not occur in water, c_{nat} = 0. When natural concentrations are not known precisely but are estimated to be low, for simplicity one may assume c_{nat} = 0. This will, however, result in an underestimated grey water footprint when c_{nat} is actually not equal to zero.

The pollutants generally consist of fertilizers (nitrogen, phosphorus, and so on), pesticides, and insecticides. One has to consider only the ‘waste flow’ to freshwater bodies, which is generally a fraction of the total application of fertilizers or pesticides to the field. One needs to account for only the most critical pollutant, that is, the pollutant in which the above calculation yields the highest water volume.

ii) Water footprint of a product

The water footprint of a product is defined as the total volume of fresh water that is used directly or indirectly to produce the product. It is estimated by considering water consumption and pollution in all steps of the production chain. In order to estimate the water footprint of a product, one will have to start by conceptualizing the way the product is produced. Thus, one will have to identify the ‘production system’. A production system consists of sequential ‘process steps’. A simplified example of the production system of a cotton shirt is: cotton growing, harvesting, ginning, carding, knitting, bleaching, dying, printing, and finishing. Given the fact that many products require multiple inputs, it is often that multiple process steps precede one next process step. In such a case, the chain of process steps is non-linear, but rather a ‘product tree’. To estimate the water footprint of a product, one will have to schematize the production system into a limited number of linked process steps. In the case of many processed goods, this might involve tracing the origin of the inputs of the product in different countries and determining the associated water footprint there. Broadly, there are two approaches to calculating the water footprint of a product:

- **The chain-summation approach**

This approach is the simplest but can be applied only in the case where a production system produces one output product (e.g., the supply chain from growing hops to making beer) as shown in Figure 2.10. In this particular case, the water footprints that can be associated with the various process steps in the production system can all be fully attributed to the product that results from the system. In this simple production system, the water footprint of the product *p* is equal to the sum of the relevant process water footprints divided by the production quantity of product:

$$WF_{prod}[p] = \frac{\sum_{s=1}^{k} WF_{proc}[s]}{P[p]} \qquad (2.10)$$

where $WF_{proc}[s]$ is the process water footprint of process step s (volume/time), and P[p] the production quantity of product *p* (mass/time). In practice, simple production systems with only one output product rarely exist; thus, a more generic way of accounting is necessary, one that can distribute the water used throughout a production system to the various output products that follow from that system without double counting.

- **The stepwise accumulative approach**

This approach is a generic way of calculating the water footprint of a product based on the water footprints of the input products that were necessary in the last processing step to produce that product and the process water footprint of that processing step. Suppose we have a number of input products when making one output product.

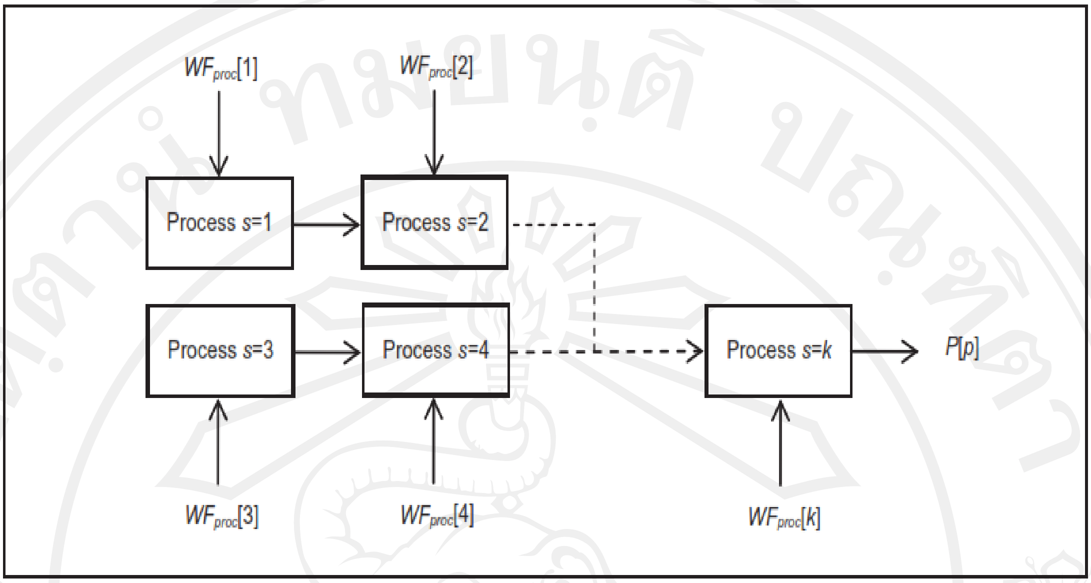

Figure 2.10 Schematization of the production system to produce one output product *p* (Source: Hoekstra et.al, 2011)

In this case, the water footprint of the output product is obtained by simply summing the water footprints of the input products and adding the process water footprint. Suppose another case where we have one input product and a number of output products. In this case, one needs to distribute the water footprint of the input product to its separate products. This can be done proportionally to the value of the output products. It could also be done proportionally to the weight of the products, but this would be less meaningful. Finally, consider the most generic case as shown in Figure 2.11. We want to calculate the water footprint of a product *p*, which is being processed from y input products. The input products are numbered from i=1 to y. Suppose that processing of the y input products results in z output products. The output products are numbered from p=1 to z.

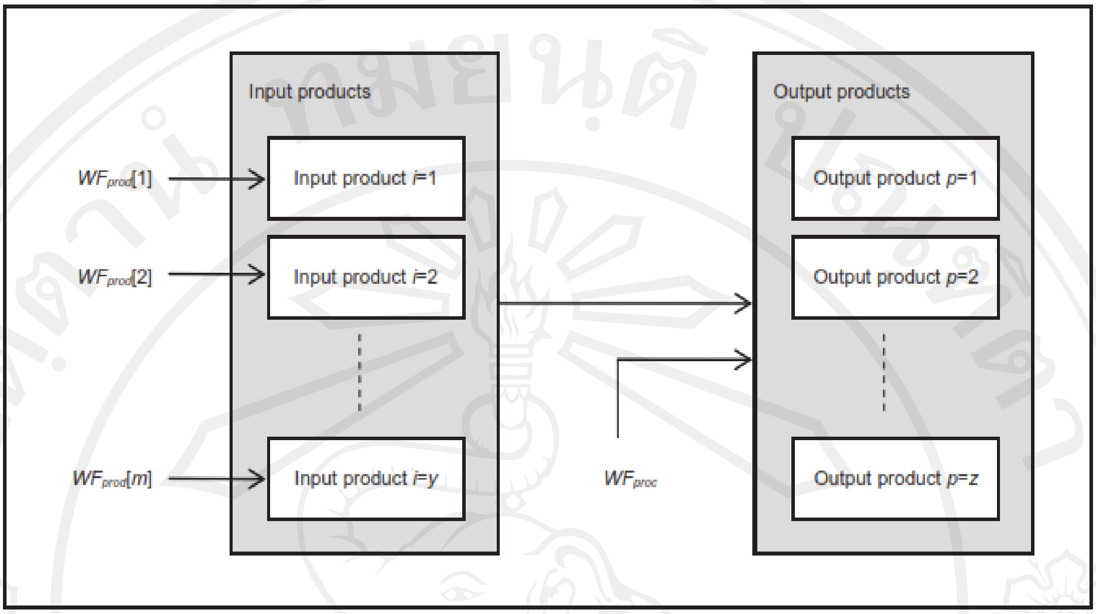

Figure 2.11 Schematization of the production system to produce product *p*.
(Source: Hoekstra et.al, 2011)

If there is some water use involved during processing, the process water footprint is added to the water footprints of the input products before the total is distributed over the various output products. The water footprint of output product *p* is calculated as:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]} \right) \times f_v[p] \qquad (2.11)$$

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

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

$$f_p[p,i] \quad = \quad \frac{w[p]}{w[i]} \qquad (2.12)$$

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

$$f_v[p] \quad = \quad \frac{price[p] \times w[p]}{\sum_{p=1}^{z}(price[p] \times w[p])} \qquad (2.139$$

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

2.3.2.3 Step 3 – Water footprint sustainability assessment

The sustainability assessment step compares the water footprint found in the accounting step to available freshwater resources for the relevant time and place. A sustainability assessment may include environmental, social and economic sustainability, as well as primary and secondary impacts. Additionally, a sustainability assessment will differ based on whether the assessment is regarding a product, or whether the assessment is regarding a geographic area. Some guidance on sustainability assessments has been developed, but this step evolved after the accounting step and thus is less developed.

The three components of sustainability considered are environmental, social and economic. If a blue, green or grey water footprint prevents any of the below from being satisfied, then the footprint is considered unsustainable.

i) Environmental sustainability: This has a quantity and a quality dimensions. Environmental flow requirements must be met in order to sustain ecosystems, groundwater flows must remain within certain limits, and water quality must remain within specified limits.

ii) Social sustainability: A minimum amount of freshwater at certain quality must be allocated to basic human needs, including drinking, washing, and cooking within a catchment or river basin. Additionally, a minimum amount of freshwater must be available for the secure production of food supply, though this consideration can look beyond the catchment or basin due to trade. If a blue, green or grey water footprint prevents the minimum amounts from being met, then the footprint is not sustainable.

iii) Economic sustainability: Water should be allocated in an economically efficient way, meaning that the benefits of the footprint should outweigh the full costs, including opportunity costs and externalities.

When considering the water footprint of production for a basin or catchment, the above can be investigated for the specified area of production. If considering the sustainability of a water footprint for a product, then the geographic origin of water inputs to that product must be identified, and a sustainability assessment must be undertaken for each geographical area.

The identification steps for the sustainability assessment are:

- Identification of the environmental, social and economic sustainability criteria
- Identification of hotspots, including particular catchments and times of the year
- Identification and quantification of the primary, or direct, impacts in the hotspots
- Identification and quantification of the secondary, or indirect, impacts in the hotspots

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

While the sustainability assessment step is intended to understand the local context of water use, the practical challenges of this task are great. The most relevant environmental, social and economic criteria to use are not identified, and what the criteria should be and how to quantify impacts is unclear. Efforts to provide more detail in this step are currently underway.

2.3.2.4 Step 4 – Water footprint response formulation

The final step in a water footprint assessment in the Water Footprint Assessment Manual is to formulate response to the water footprint. In theory, if a water footprint is deemed unsustainable, action should be taken to reduce the water footprint and make it sustainable.

The suite of responses possible will depend on the entity or group responding. The entity which will be responding should be identified in the goal-setting phase of the water footprint, and may include consumers, companies, investors or government.

What constitutes an appropriate response or suite of responses is in the very early stages of development. Many ideas for responses have been suggested for consumers, companies, government, and investors. For example, farmers and agricultural policy-makers can seek to support efficient farming practices, and retailers or food and beverage companies can engage with their suppliers to encourage efficient practices. Nonetheless, these suggestions are very simplified. It is unclear how a water footprint actually informs the choice of which response is most appropriate, and what makes these responses different from generally good water management practices. Efforts are underway to develop the understanding of response options.

2.4 Scenario analysis

Scenario analysis is a process of analyzing possible future events by considering alternative possible outcomes (sometimes called "alternative worlds"). Thus, the scenario analysis, which is a main method of projections, does not try to show one exact picture of the future. Instead, it presents several alternative future developments. Consequently, a scope of possible future outcomes is observable. Not only are the outcomes observable but also the development paths leading to the outcomes. In contrast to prognoses, the scenario analysis is not using extrapolation of the past. It does not rely on historical data and does not expect past observations to be valid in the future. Instead, it tries to consider possible developments and turning points, which may only be connected to the past. In short, several scenarios are demonstrated in a scenario analysis to show possible future outcomes. It is useful to generate a combination of an optimistic, a pessimistic, and a most likely scenario. Although widely argued, experience has shown that three scenarios are most appropriate for further discussion and selection. More scenarios could make the analysis unclear (Wikipedia, 2013).

The general phases of scenario process consist of five phases (Hannah Kosow and Robert Gaβner, 2008): 1) identification of the scenario field, 2) identification of key factors, 3) analysis of the key factors, 4) scenario generation, and, if necessary, 5) scenario transfer, as shown in Figure 2.12.

The first step in every scenario process is to define precisely for what purpose scenarios are to be developed. Examples of the questions to ask are: What specifically is the issue here? What is the topic? What problem is to be dealt with? How is the scenario field to be defined? What must be integrated? Of equal importance, where are the limits, that is, what is to be left out of consideration? This thought corresponds for the most part with the definition of the object to be researched and the definition of topics in other research designs; in its degree of concreteness, however, it even goes to some extent beyond them.

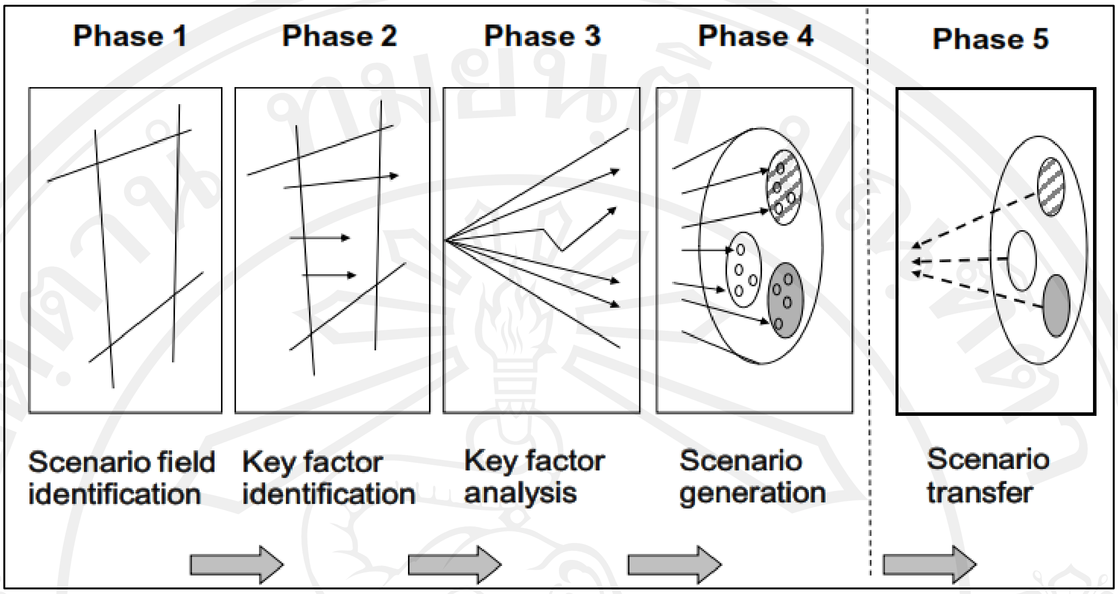

Figure 2.12 The five phases of general scenario process (Hannah Kosow and Robert Gaβner, 2008)

The second phase involves working out a description of the scenario field in terms of its key factors, or “descriptors“, as they are sometimes called. These are the central factors which together form a description of the scenario field while also having an impact on the field itself and/or serving as a means for the field to have an impact on the world around it. Key factors are thus those variables, parameters, trends, developments, and events which receive central attention during the further course of the scenario process. Identification of these key factors requires knowledge of the scenario field as such and its interactions with the various key factors.

This brings us to the third step which is especially typical of scenario techniques and sets them apart from other methods: the widening scenario “funnel” in which individual key factors are subjected to analysis to find what possible future salient characteristics are conceivable in each case. An individual “funnel opening into the future“, so to speak, widens out for each factor inasmuch as those salient characteristics are selected which are to become part of the budding scenario. Although this step can be carried out in numerous ways, it always contains intuitive and creative aspects; these are essential for visualizing the various future developments of any key factor.

In the fourth phase, scenarios are generated by singling them out and condensing them from the "cross section" of the scenario funnel whose opening extends to the selected projection point in the future. This is where consistent bundles of factors are brought together, selected, and worked up into scenarios. However, major differences in method are also found at this step. The process by which the "condensation" into scenarios takes place may extend from narrative literary procedures all the way to formalized, mathematical techniques. In addition, a sorting out of scenarios is required in many scenario techniques. Even though many scenarios are often theoretically conceivable, the number of scenarios which can be processed cognitively is limited.

The last phase involves a description of the further application and/or processing of scenarios which have been generated. According to Van der Heijden (2005), effective scenario planning requires the following five characteristics:

- At least two scenarios are needed to reveal the degree of inherent uncertainty in the model simulation. The use of more than four scenarios is proven to be impractical and counterproductive.
- Scenarios must be plausible, conceivable and representative of the current status of knowledge regarding the issue under investigation.
- Scenario must be internally consistent.
- Scenarios must be relevant to the aim of the investigation.
- Scenarios must generate a new perspective regarding the issues that are investigated.