OF WATER FOR
DRINKING, COOKING
AND WASHING, BUT
EVEN MORE FOR
PRODUCING THINGS
SUCH AS FOOD, PAPER,
COTTON CLOTHES,
ETC. THE WATER
FOOTPRINT IS AN
INDICATOR OF WATER
USE THAT LOOKS AT
BOTH DIRECT AND
INDIRECT WATER USE
OF A CONSUMER
OR PRODUCER. THE
WATER FOOTPRINT
OF AN INDIVIDUAL,
COMMUNITY OR
BUSINESS IS DEFINED
AS THE TOTAL VOLUME
OF FRESHWATER THAT
IS USED TO PRODUCE
THE GOODS AND
SERVICES CONSUMED
BY THE INDIVIDUAL
OR COMMUNITY OR
PRODUCED BY THE
BUSINESS.

WATER FOOTPRINT MANUAL

State of the Art 2009

Arjen Y. Hoekstra

Ashok K. Chapagain

Maite M. Aldaya

Mesfin M. Mekonnen

Water Footprint
NETWORK

Water Footprint

WATER FOOTPRINT MANUAL

State of the Art 2009

Arjen Y. Hoekstra[1,2,4]

Ashok K. Chapagain[3]

Maite M. Aldaya[1,2]

Mesfin M. Mekonnen[2]

[1] Water Footprint Network, Enschede, Netherlands

[2] University of Twente, Enschede, Netherlands

[3] WWF-UK, Godalming, UK

[4] Corresponding author: a.y.hoekstra@utwente.nl

Contents

Preface

Many individuals and organisations have asked the Water Footprint Network for a manual that contains a complete, consistent and up-to-date overview of the method of water footprint assessment. This report offers such a manual. It covers a comprehensive set of methods for water footprint accounting. It shows how water footprints cane be calculated for individual processes and products, as well as for consumers, nations and businesses. Besides, the report includes methods for water footprint sustainability assessment and a library of water footprint response options. This manual has been prepared by the authors as requested by the Water Footprint Network and serves as the water footprint guidelines promoted by the WFN.

The current manual is a first version. It will be a living document, requiring frequent updates and improvement. Since all over the world research in this area is rapidly developing and given that recently various pilot studies on water footprint assessment have started and that many others are expected to follow, we anticipate that the document will need an update in one year time from now. In order to safeguard optimal learning from the various ongoing practical water footprint pilot projects and from expected new scientific publications, the Water Footprint Network plans to organize the production of the second version of the manual along the following process:

1. all partners of the Water Footprint Network are invited to provide feedback on this version of the manual.
2. on the basis of feedbacks received – new scientific publications, experiences from practical water footprint pilots and working group reports – the Water Footprint Network will prepare a draft of a second version.
3. the Water Footprint Peer Review Committee takes into account all comments and new insights to recommend revisions of the draft.
4. the draft second-version manual is revised into a final second-version manual.

The second version will be published in a year from now. And then we will start the cycle again in the direction of a third version. In this way we hope to make best use of the diverse experiences that our partners will have when using the water footprint within different contexts and for different purposes. We aim to further refine the water footprint methodology such that it best serves the various purposes that different sectors in society see for it, at the same time striving for coherence, consistency and scientific scrutiny. I hereby invite you to provide us with your suggestions and comments on this current manual based on your own studies and experience.

Derk Kuiper
Executive Director
Water Footprint Network

1. Introduction

1.1. Background

Various human activities consume or pollute a lot of water. At a global scale, most of the water use occurs in agricultural production, but there are also substantial water volumes consumed and polluted in the industrial and domestic sectors (WWAP, 2009). Water consumption and pollution can be associated with specific activities, such as irrigation, bathing, washing, cleaning, cooling and processing. Total water consumption and pollution are generally regarded as the sum of a multitude of independent water demanding and polluting activities. There has been little attention to the fact that, in the end, total water consumption and pollution relate to what and how much communities consume and to the structure of the global economy that supplies the various consumer goods and services. Until the recent past, there have been few thoughts in the science and practice of water management about water consumption and pollution along whole production and supply chains. As a result, there is little awareness about the fact that the organisation and characteristics of a production and supply chain does actually strongly influence the volumes (and temporal and spatial distribution) of water consumption and pollution that can be associated with a final consumer product. Hoekstra and Chapagain (2008) have shown that visualizing the hidden water use behind products can help in understanding the global character of fresh water and in quantifying the effects of consumption and trade on water resources use. The improved understanding can form a basis for a better management of the globe's freshwater resources.

Fresh water is increasingly becoming a global resource, driven by growing international trade in goods and services. Apart from regional markets, there are also global markets for water-intensive goods like crop and livestock products, natural fibres and bio-energy. As a result, use of water resources has become spatially disconnected from the consumers. This can be illustrated for the case of cotton. From field to end product, cotton passes through a number of distinct production stages with different impacts on water resources. These stages of production are often located in different places and final consumption can be in yet another place. For example, Malaysia does not grow cotton, but imports raw cotton from China, India and Pakistan for processing in the textile industry and exports cotton clothes to the European market (Chapagain et al., 2006b). As a result, the impacts of consumption of a final cotton product on the globe's water resources can only be found by looking at the supply chain and tracing the origins of the product. Uncovering the hidden link between consumption and water use can form the basis for the formulation of new strategies of water governance, because new triggers for change can be identified. Where final consumers, retailers, food industries and traders in water-intensive products have traditionally been out of the scope of those who studied or were responsible for good water governance, these players enter the picture now as potential 'change agents'. They can be addressed now not only in their role as *direct* water user, but also in their role as *indirect* water user.

1.2. The water footprint concept

The idea of considering water use along supply chains has gained interest after the introduction of the 'water footprint' concept by Hoekstra in 2002 (Hoekstra, 2003). The water footprint 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. The water footprint can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally. The blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product. 'Consumption' refers to loss of water from the available ground-surface water body in a catchment area, which happens when water evaporates, returns to another catchment area or the sea or is incorporated into a product. The green water footprint refers to consumption of green water resources (rainwater stored in the soil as soil moisture). The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.
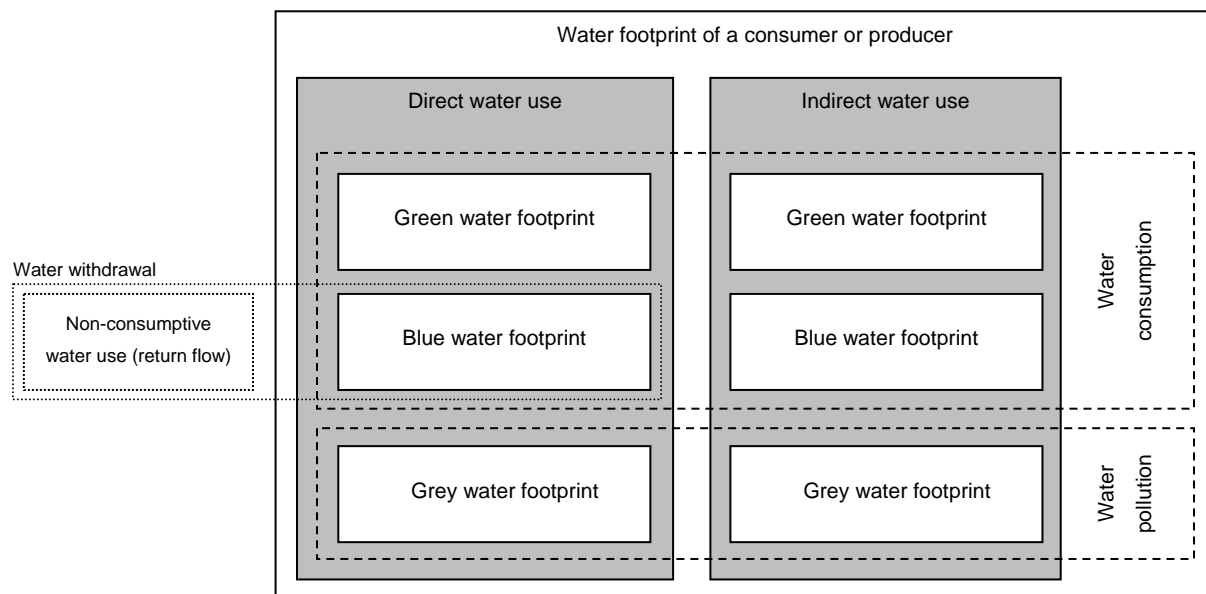
Figure 1.1. *Schematic representation of the components of a water footprint. It shows that the non-consumptive part of water withdrawals (the return flow) is not part of the water footprint. It also shows that, contrary to the measure of 'water withdrawal', the 'water footprint' includes green and grey water and the indirect water-use component.*

As an indicator of 'water use', the water footprint differs from the classical measure of 'water withdrawal' in three respects (Figure 1.1):

- it is not restricted to blue water use, but also includes green and grey water.
- it is not restricted to direct water use, but also includes indirect water use.

- it does not include blue water use insofar this water is returned to where it came from.

The water footprint thus offers a wider perspective on how a consumer or producer relates to the use of freshwater systems. It is a volumetric measure of water consumption and pollution. It is *not* a measure of the severity of the local environmental impact of water consumption and pollution. The local environmental impact of a certain amount of water consumption and pollution depends on the vulnerability of the local water system and the number of water consumers and polluters that make use of the same system. Water footprint accounts give spatiotemporally explicit information on how water is appropriated for various human purposes. They can feed the discussion about sustainable and equitable water use and allocation and also form a good basis for a local assessment of environmental, social and economic impacts.

1.3. The four phases in water footprint assessment

A full water footprint assessment consists of four distinct phases (Figure 1.2):

- setting goals and scope
- water footprint accounting
- water footprint sustainability assessment
- water footprint response formulation.

Phase 1	Phase 2	Phase 3	Phase 4
Setting goals and scope	Water footprint accounting	Water footprint sustainability assessment	Water footprint response formulation
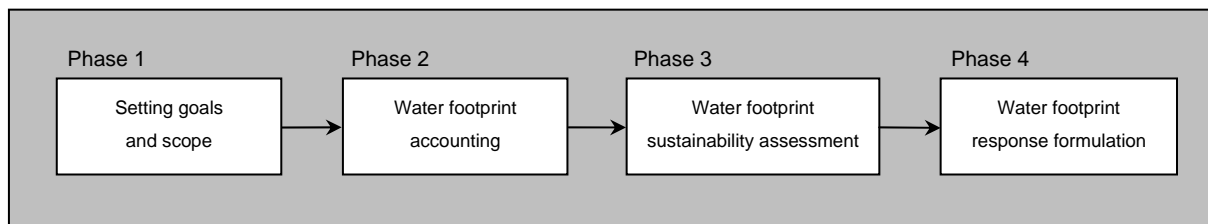
Figure 1.2. Four distinct phases in water footprint assessment: (1) setting goals and scope; (2) water footprint accounting; (3) water footprint sustainability assessment; (4) formulation of response.

In order to be transparent about the choices made when undertaking a water footprint assessment study, one will have to start with clearly setting the goals and scope of the study. A water footprint study can be undertaken for many different reasons. For example, a national government may be interested in knowing its dependency on foreign water resources or it may be interested to know the sustainability of water use in the areas where water-intensive import products come from. A river basin authority may be interested to know whether the aggregated water footprint of human activities within the basin violates environmental flow requirements or water quality standards at any time. The river basin authority may also want to know to what extent scarce water resources in the basin are allocated to low-value export crops. A company may be interested to know its dependence on scarce water resources in its supply-chain or how it can contribute to lower the impacts on water systems throughout its supply chain and within its own operations.

The phase of water footprint accounting is the phase in which data are collected and accounts are developed. The scope of and level of detail in the accounting depends on the decisions made in the previous phase. After the accounting phase follows the phase of sustainability assessment, in which the water footprint is evaluated from an environmental perspective, as well as from a social and economic perspective. In the final phase, response options, strategies or policies are formulated. It is not necessary to include all steps in one study. In the first phase of setting goals and scope one can decide to focus on accounting only or stop after the phase of sustainability assessment, leaving the discussion about response for later. Besides, in practice, this model of four subsequent phases is more a guiding ideal than a strict directive. Returning to earlier steps and iteration of phases will often be necessary. In first instance, a company may be interested in a rough exploration of all phases, in order to identify hotspots and priorities, while later on it may like to seek much greater detail in certain areas of the accounts and the sustainability assessment.

1.4. Guide for the reader

The four phases of water footprint assessment are addressed in the following chapters:

- Chapter 2: setting goals and scope
- Chapter 3: water footprint accounting
- Chapter 4: water footprint sustainability assessment
- Chapter 5: water footprint response formulation.

Chapter 6 identifies and discusses the major challenges to be addressed in the future. Chapter 7 is the concluding chapter. Depending on the interest of the reader, one can focus on different parts of the manual. Particularly in Chapter 3 on water footprint accounting, the reader can be selective. The following sections are most relevant depending on the interest:

- consumers: 3.1 – 3.2 – 3.3 – 3.4.
- river basin authorities: 3.1 – 3.2 – 3.3 – 3.5.
- national governments: 3.1 – 3.2 – 3.3 – 3.6.
- businesses: 3.1 – 3.2 – 3.3 – 3.7.

One will see that the basics of water footprint accounting – process and product accounts (Sections 3.2 and 3.3) – are relevant for all water footprint applications.

2. Goals and scope of water footprint assessment

2.1. Goals of water footprint assessment

Water footprint studies may have various purposes and applied in different contexts. Each purpose requires its own scope of analysis and will allow for different choices when making assumptions. A checklist for defining the goal of water footprint assessment is given in Box 2.1. The list is not exhaustive but rather shows a number of different options. Probably the most important question is what sort of detail one seeks. If the purpose is awareness raising, national or global average estimates for the water footprints of products are probably sufficient. When the goal is hotspot identification, one will need to include a greater detail in the scope and subsequent accounting and assessment, so that it is possible to exactly pinpoint where and when the water footprint has most environmental, social or economic impacts. If the aim is to formulate policy and establish targets on quantitative water footprint reduction, an even higher degree of spatial and temporal detail is required. Besides, one will have to embed the water footprint assessment in a broader deliberation incorporating factors other than water alone.

Box 2.1. *Goals of water footprint assessment – A checklist.*

General

- What is the ultimate target? Awareness raising, hotspot identification, policy formulation or quantitative target setting?
- Is there a focus on one particular phase? Focus on accounting, sustainability assessment or response formulation?
- What is the scope of interest? Direct and/or indirect water footprint? Green, blue and/or grey water footprint?
- How to deal with time? Aiming at assessment for one particular year or at the average over a few years, or trend analysis?

Product water footprint assessment

- What product to consider? One stock-keeping unit of a particular brand, one particular sort of product, or a whole product category?
- What scale? Include product(s) from one field or factory, one or more companies, or one or more production regions?

Consumer or community water footprint assessment

- Which community? One individual consumer or the consumers within a municipality, province or state?

Assessment of the water footprint within a geographically delineated area

- What are the area boundaries? A catchment, river basin, municipality, province, state or nation?
- What is the field of interest? Assess the virtual-water balance of the area (to examine how the water footprint within the area is reduced by importing virtual water and how the water footprint within the area is increased by making products for export), analyse how the area's water resources are allocated over various purposes, and/or examine where the water footprint within the area violates local environmental flow requirements and ambient water quality standards.

National water footprint assessment (water footprint within a nation and water footprint of national consumption)

- What is the scope of interest? Assess the water footprint within a nation and/or the water footprint of national consumption? Analyse the internal and/or the external water footprint of national consumption?
- What is the field of interest? Assess national water scarcity, sustainability of national production, export of scarce water resources in virtual form, national water saving by import of water in virtual form, sustainability of national consumption, impacts of the water footprint of national consumption in other countries and/or dependency on foreign water resources?

Business water footprint assessment

- What is the scale of study? A company unit, whole company or a whole sector? (when the scale of interest is the product level, see above under product water footprint assessment)
- What is the scope of interest? Assess the operational and/or the supply-chain water footprint?
- What is the field of interest? Business risk, product transparency, corporate environmental reporting, product labelling, bench-marking, business certification, hotspot identification, formulation of quantitative reduction targets, or offsetting remaining impacts?

2.2. Inventory boundaries of water footprint accounting

One will have to be clear and explicit about the inventory boundaries when setting up a water footprint account. The boundaries may be chosen depending on the purpose of setting up the account. One can use at least the following checklist when setting up a water footprint account:

- consider blue, green and/or grey water footprint?
- where to truncate the analysis when going back along the supply chain?
- which level of spatiotemporal explication?
- which period of data?
- for consumers and businesses: consider direct and/or indirect water footprint?
- for nations: consider water footprint within the nation and/or water footprint of national consumption; consider internal and/or external water footprint of national consumption?

Blue, green and/or grey water footprint?
Blue water resources are generally scarcer and have higher opportunity cost than green water, so that may be a reason to focus on accounting the blue water footprint only. On the other hand, also green water resources are limited and thus scarce, which gives an argument to account the green water footprint as well. Besides, green water can be substituted by blue water and sometimes – particularly in agriculture – the other way around as well, so that a complete picture can be obtained only by accounting for both. The argument for including green water use is that the historical engineering focus on blue water has led to the undervaluation of green water as an important factor of production (Falkenmark, 2003; Rockström, 2001). The idea of the grey water footprint was introduced in order to express water pollution in terms of a volume polluted, so that it can be compared with water consumption, which is also expressed as a volume (Chapagain et al., 2006; Hoekstra and Chapagain, 2008). If one is interested in water pollution and in comparing the relative claims of water pollution and water consumption on the available water resources, it is relevant to account the grey in addition to the blue water footprint.

Where to truncate the analysis when going back along the supply chain?
The truncation issue is a basic question in water footprint accounting. One faces similar questions as in carbon and ecological footprint accounting, energy analysis and life cycle assessment. No general guidelines have been developed yet in the field of water footprint accounting, but the general rule is: include the water footprint of all processes within a production system (production tree) that 'significantly' contribute to the overall water footprint. The question remains what 'significant' is; one can say for instance 'larger than 1%' (or 'larger than 10%' when interested in the largest components only). If one traces the origins of a particular product, one will see that supply chains are never-ending and widely diverging because of the variety of inputs used in each process step. In practice, however, there are only a few process steps that substantially contribute to the total water footprint of the final product. As a rule of thumb, one can expect that when a product includes ingredients that originate from agriculture, those ingredients often give a major contribution to the overall water footprint of

the product. This is the case because an estimated 86% of the water footprint of humanity is within the agricultural sector (Hoekstra and Chapagain, 2008). Industrial ingredients are likely to contribute particularly when they can be associated with water pollution (so they will contribute to the grey water footprint).

A specific question that falls under the truncation issue is whether one should account for the water footprint of labour, which is an input factor in nearly all processes. The argument could be made that employees are an input factor that requires food, clothing and drinking water, so that all the direct and indirect water requirements of employees should be included in the indirect water footprint of a product. However, this creates a very serious accounting problem, well-known in the field of life cycle analysis. The problem is that double counting would occur. The underlying idea of natural resources accounting of products is to allocate all natural resource use to the final consumer products and based on consumption data to consumers. All natural resource use is thus ultimately attributed to consumers. Consumers are, however, also workers. It would create a never-ending loop of double, triple counting etc. when the natural resource use attributed to a consumer would be counted as natural resource use underlying the input factor labour in production. In short, it is common practice to exclude labour as a factor embodying indirect resource use.

Another specific question often posed – particularly by analysts who have experience with carbon footprint accounting – is whether the water footprint of transport should be included. The general answer is: no. Transport costs a lot of energy, the amount of which may constitute a significant component of the overall energy used to produce a product and get it to its final destination. Transport, however, does not consume a significant amount of freshwater. We recommend including the water footprint of transport only when biofuels are used as the source of energy. More in general, one can ask whether the water footprint of energy applied in a production system should be included in the assessment of the water footprint of the final product. Again, in most cases the contribution of the factor energy will be a small percentage of the overall water footprint of a product. An exception may be when energy is sourced from biofuel or from electricity from biomass combustion or hydropower, because those forms of energy have a relatively large water footprint per unit of energy (Gerbens et al., 2009a,b).

Which level of spatiotemporal explication?
Water footprints can be assessed at different levels of spatiotemporal detail (Table 2.1). At level A, the lowest level of detail, the water footprint is assessed based on global average water footprint data from an available database. This level of detail is sufficient and even most instrumental for the purpose of awareness raising. This level of detail can also be suitable when the aim is to identify products and ingredients that most significantly contribute to the overall water footprint. Global-average water footprint data can also be useful for developing rough projections of future global water consumption given major changes in consumption patterns (like a shift towards more meat or bio-energy). At level B, the water footprint is assessed based on national or regional average or catchment-specific water footprint data from an available geographically explicit database. This level of accounting is suitable to provide a basis for understanding where hotspots in local watersheds can be expected and for making water allocation decisions. At level C, water footprint accounts are geographically and

temporally explicit, based on precise data on inputs used, and precise sources of those inputs. The minimum spatial resolution is the level of small catchments (~100 km^2). The minimum temporal resolution is a month. The accounting is based on best estimates of actual local water consumption and pollution, preferably verified on the ground. This high level of spatiotemporal detail is suitable for formulating site-specific water footprint reduction strategies.

Table 2.1. *Spatiotemporal explication in water footprint accounting.*

	Spatial explication	Temporal explication	Source of required data on water use	Typical use of the accounts
Level A	Global average	Annual	Available literature and databases on typical water consumption and pollution by product or process	Awareness raising; rough identification of components contributing most to the overall water footprint; development of global projections of water consumption
Level B	National, regional or catchment specific	Annual or monthly	As above, but use of nationally, regionally or catchment specific data	Rough identification of spatial spreading and variability; knowledge base for hotspot identification and water allocation decisions
Level C	Locally, site and field specific	Monthly or daily	Empirical data or (if not directly measurable) best estimates on water consumption and pollution, specified by location and over the year	Knowledge base for carrying out a water footprint sustainability assessment; formulation of a strategy to reduce water footprints and associated local impacts

Note: the three levels can be distinguished for all forms of water footprint accounting (product, national, corporate accounts).

Which period of data?

Water availability fluctuates within a year and across years as well. As a consequence of varying water availability, water demand varies in time as well. One should thus be extremely cautious in making claims about a water footprint trend in time. Whatever water footprint study is undertaken, one should be explicit about the period of data used, because the period chosen will affect the outcome. In dry years, the blue water footprint of a crop product will be much higher than in wet years, because more irrigation water will be required. One can choose to calculate water footprints for one particular year or a number of specific years, but alternatively one can choose to calculate the water footprint under an average year given the existing climate (defined as the average over a consecutive period of 30 years). In the latter case one will combine different periods in one analysis: one takes for example production and yield data for a recent period of five years but data on climate (temperature and precipitation) as an average for the past 30 years.

Direct and/or indirect water footprint?

The general recommendation is to include both direct and indirect water footprint. By addressing only their direct water footprint, consumers would neglect the fact that the largest part of their water footprint is associated with the products they buy, not the water they consume at home. For most businesses, the water footprint in their supply-chain is much bigger than the water footprint of their own operations; ignoring the supply chain component may lead to investments in making improvements in the operational water use while investments in

improving the supply chain could have been more cost effective. Depending on the purpose of a particular study, however, one can of course decide to include only the direct or indirect water footprint in the analysis. There is some similarity here with the 'scopes' as distinguished in carbon footprint accounting (see Box 2.2).

Box 2.2. Are there 'scopes' in water footprint accounting like in the case of corporate carbon footprint accounting?

A carbon footprint is the total set of greenhouse gas (GHG) emissions caused directly and indirectly by an individual, organization, event or product. In the field of corporate carbon footprint accounting, three 'scopes' have been defined (WRI and WBCSD, 2004). Scope 1 refers to the accounting of 'direct' GHG emissions, which occur from sources that are owned or controlled by the company. Examples: emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment. Scope 2 refers to accounting of 'indirect' GHG emissions from the generation of purchased electricity consumed by the company. Scope 3 refers to other indirect GHG emissions, which are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Examples of scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services. The distinction between 'direct' and 'indirect' is also made in case of water footprint accounting. The total water footprint of a consumer or producer refers, by definition, to both the direct and the indirect water use of this consumer or producer. This means that, without specification, the term water footprint refers to the sum of direct and indirect. The distinction between scopes 2 and 3 as applied in carbon footprint accounting is not useful in the case of water footprint accounting. In water footprint accounting there are thus two 'scopes' only: 'direct' and 'indirect' water footprint.

Consider the water footprint within a nation or the water footprint of national consumption?

The 'water footprint within a nation' refers to the total freshwater volume consumed or polluted within the territory of the nation. This includes water use for making products consumed domestically but also water use for making export products. The 'water footprint within a nation' is different from the 'water footprint of national consumption', which refers to the total amount of water that is used to produce the goods and services consumed by the inhabitants of the nation. This refers to both water use within the nation and water use outside the territory of the nation, but is restricted to the water use behind the products consumed within the nation. The water footprint of national consumption thus includes an internal and an external component. Including an analysis of the external water footprint is key in order to get a complete picture of how national consumption translates to water use not only in the own country but also abroad, and thus to analyse water dependency and sustainability of imports. Looking at the water footprint within a nation is sufficient when the interest lies with the use of domestic water resources only.

2.3. Inventory boundaries of water footprint sustainability assessment

The sustainability of a water footprint can be viewed upon from different perspectives: the environmental, social and economic perspective. Besides, sustainability can be measured at different levels: there can be local impacts (e.g. violation of local environmental flow requirements), but there can also be impacts at catchment or river-basin level (e.g. contribution to the violation of environmental flow requirements downstream). In addition, the water footprint of a product has implications beyond the level of a particular river basin. Since freshwater resources at the level of a larger political region or the world as a whole is scarce, a limited number of purposes can be served. Allocation of water to one purpose withdraws from the possibility to allocate it for another purpose. The water footprints of products like meat, bio-energy or cut flowers can press in catchments where

water is abundantly available and where local environmental flow requirements are not violated, but the global implications of these water footprints are that less water remains to be allocated to other purposes, such as growing cereal crops to fulfil basic food demand.

The boundaries applied in the phase of water footprint sustainability assessment may be chosen depending on the goal of the assessment. In this respect, there are at least two basic questions:

- consider environmental, social and/or economic aspects?
- consider sustainability at local, basin and/or global level?

Assessing the sustainability of a water footprint will depend on a multitude of criteria. An important question will therefore be which criteria will be used and how to compare (or even weigh) different criteria. There is neither one best set of criteria nor one best way to determine the relative importance of the different criteria. One can, however, categorise criteria in a logical way and, once certain criteria have been chosen and clearly defined, they can be empirically assessed.

3. Water footprint accounting

3.1. Coherence between different sorts of water footprint accounts

The water footprint of one single 'process step' is the basic building block of all water footprint accounts (see Figure 3.1 and Box 3.1). The water footprint of an intermediate or final 'product' is the aggregate of the water footprints of the various process steps relevant in the production of the product. The water footprint of an individual consumer is a function of the water footprints of the various products consumed by the consumer. The water footprint of a community of consumers – e.g. the inhabitants of a municipality, province, state or nation – is equal to the sum of the individual water footprints of the members of the community. The water footprint of a producer or whatever sort of business is equal to the sum of the water footprints of the products that the producer or business delivers. The water footprint within a geographically delineated area – be it a province, nation, catchment area or river basin – is equal to the sum of the water footprints of all processes taking place in that area. The total water footprint of humanity is equal to the sum of the water footprints of all consumers of the world, which is equal to the sum of the water footprints of all final consumer goods and services consumed annually and also equal to the sum of all water-consuming or polluting processes in the world.
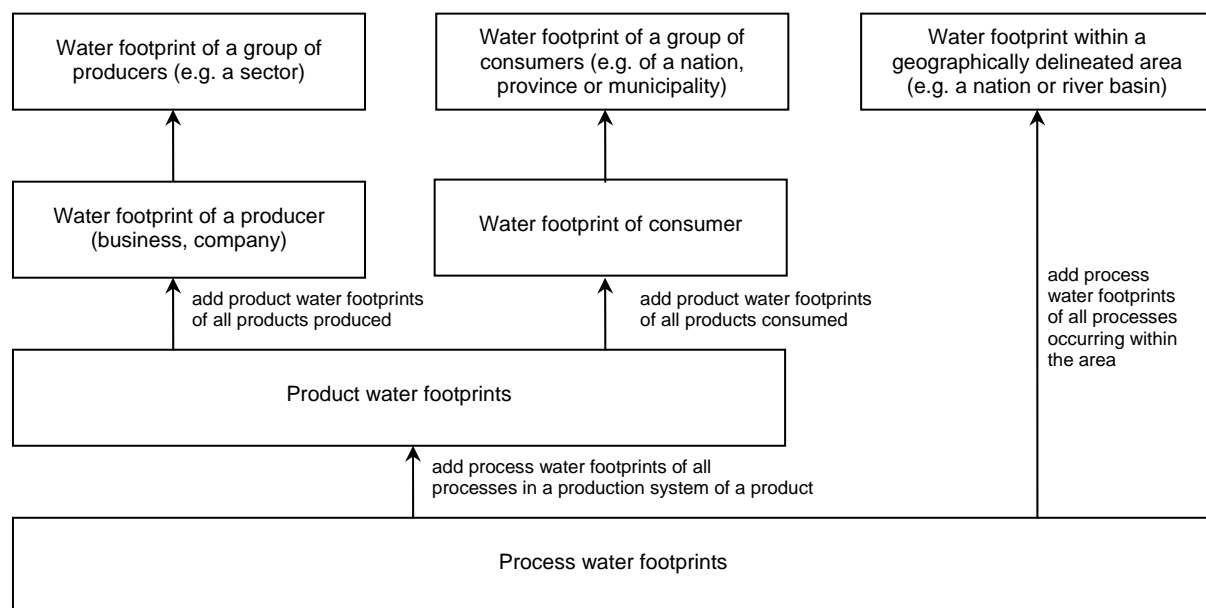
Figure 3.1. *Process water footprints as the basic building block for all other water footprints.*

Water footprints of final (consumer) products can be added without double counting. This is due to the fact that process water footprints are always exclusively allocated to one final product, or, when a process contributes to more than one final product, a process water footprint is divided over the different final products. Adding water footprints of intermediate products does not make sense, because double counting can easily occur. If one would add, for instance, the water footprint of cotton fabric and the water footprint of harvested cotton, one would double count, because the former includes the latter. Similarly, one can add the water footprints of individual consumers without double counting, but not the water footprints of different producers.

- The water footprint of a product = the sum of the water footprints of the process steps taken to produce the product (considering the whole production and supply chain).
- The water footprint of a consumer = the sum of the water footprints of all products consumed by the consumer.
- The water footprint of a community = the sum of the water footprints of its members.
- The water footprint of national consumption = the sum of the water footprints of its inhabitants.
- The water footprint of a business = the sum of the water footprints of the final products that the business produces.
- The water footprint within a geographically delineated area (e.g. a municipality, province, state, nation, catchment or river basin) = the sum of the process water footprints of all processes taking place in the area.

The water footprint of consumers is related to the water footprints of the producers in the supply-chain. Figure 3.2 shows a simplified example of the supply-chain of an animal product. The total water footprint of a consumer is the sum of its direct and indirect water footprint. When we focus on meat consumption, the direct water footprint of the consumer refers to the volume of water consumed or polluted when preparing and cooking the meat. The indirect water footprint of the meat consumer depends on the direct water footprints of the retailer that sells the meat, the food processor that prepares the meat for sale, the livestock farm that raises the animal and the crop farm that produces the feed for the animal. The indirect water footprint of the retailer depends on the direct water footprints of the food processor, livestock farm and crop farm, etc.

The 'water footprint of the consumers in an area' is not equal to the 'water footprint within the area', but they are related. Figure 3.3 shows the relation between the water footprint of national consumption and the water footprint within a nation in a simplified example for two trading nations. The 'internal' water footprint of national consumption is equal to the water footprint within the nation insofar not related to producing export products. The 'external' water footprint of national consumption can be found by looking at the import of products (and thus water in virtual form) and the associated water footprint within another nation.

A water footprint is expressed in terms of a water volume per unit of product or as a water volume per unit of time (Box 3.2). The water footprint of a process is expressed as water volume per unit of time. When divided over the quantity of product that results from the process, it can also be expressed as water volume per product unit. A product water footprint is always expressed in terms of water volume per unit of product (usually m^3/ton or litre/kg). The water footprint of a consumer or producer or the water footprint within an area is always expressed as water volume per unit of time. Depending on the level of detail that one aims to provide, the water footprint can be expressed per day, month or year.
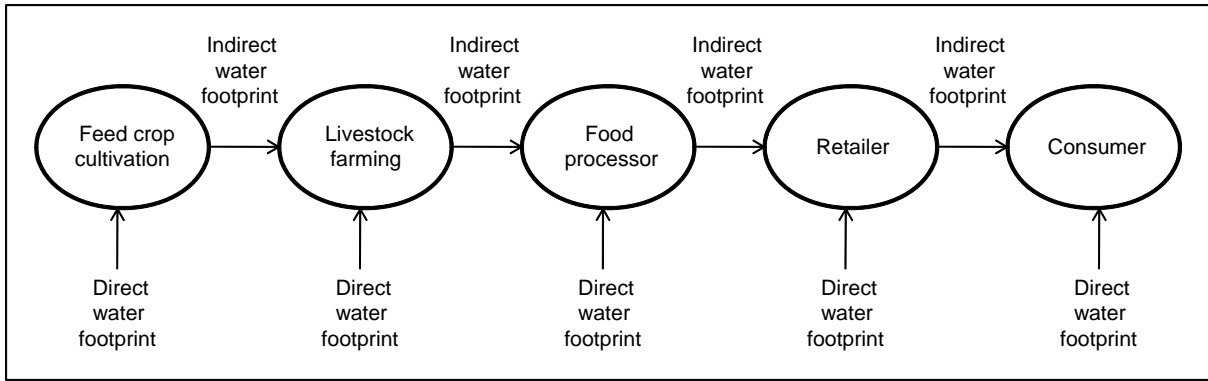
Figure 3.2. *The direct and indirect water footprint in each stage of the supply chain of an animal product.*
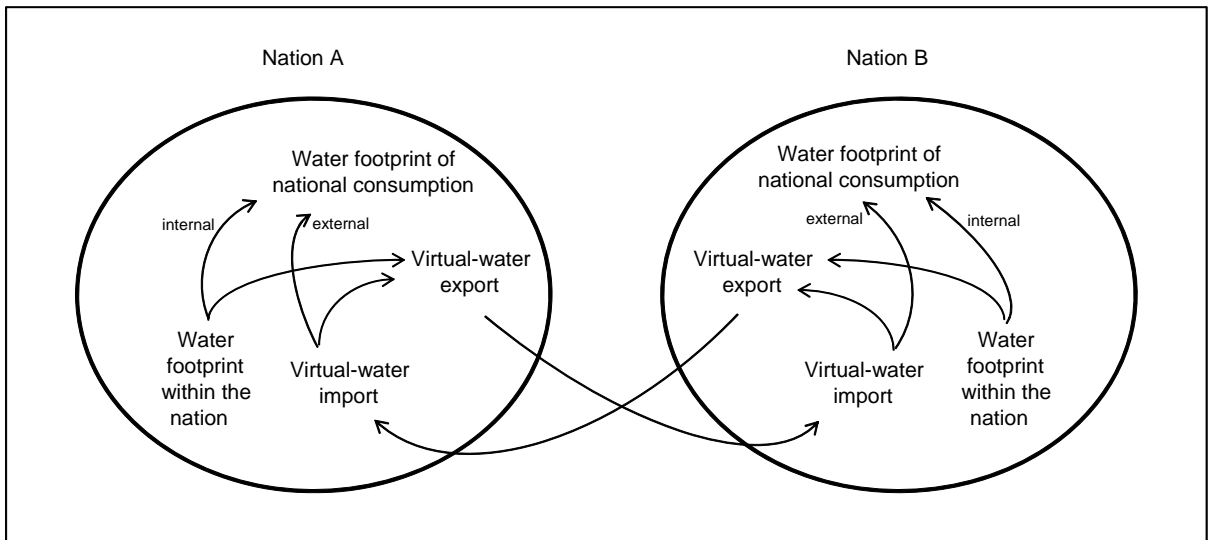
Figure 3.3. *The relation between the water footprint of national consumption and the water footprint within a nation in a simplified example for two trading nations.*

Box 3.2. *The unit of a water footprint.*

- The water footprint of a process is expressed as water volume per unit of time. When divided over the quantity of product that results from the process (product units per unit of time), it can also be expressed as water volume per product unit.
- The water footprint of a product is always expressed as water volume per product unit. Examples:
  - water volume per unit of mass (for products where weight is a good indicator of quantity)
  - water volume per unit of money (for products where value tells more than weight)
  - water volume per piece (for products that are counted per piece rather than weight)
  - water volume per unit of energy (per kcal for food products, or per joule for electricity or fuels)
- The water footprint of a consumer or business is expressed as water volume per unit of time. It can be expressed as water volume per monetary unit when the water footprint per unit of time is divided by income (for consumers) or turnover (for businesses). The water footprint of a community of consumers can be expressed in terms of water volume per unit of time per capita.
- The water footprint within a geographically delineated area is expressed as water volume per unit of time. It can be expressed in terms of water volume per monetary unit when divided over the income in the area.

3.2. Water footprint of a process step

3.2.1. Blue water footprint

The blue water footprint is an indicator of consumptive use of so-called blue water, i.e. fresh surface or groundwater. The term 'consumptive water use' refers to one of the following four cases:

- water evaporates;
- water is incorporated into the product;
- water does not return to the same catchment area, e.g. it is returned to another catchment area or the sea;
- water does not return in the same period, e.g. it is withdrawn in a scarce period and returned in a wet period.

The first component, evaporation, is generally the most significant one. Therefore one will often see that consumptive use is equated with evaporation, but the other three components should be included when relevant. 'Consumptive water use' does not mean that the water disappears, because most water at earth remains within the cycle and always returns somewhere. Water is a renewable resource, but that does not mean that its availability is unlimited. In a certain period, the amount of water that recharges groundwater reserves and that flows through a river is always limited to a certain amount. Water in rivers and aquifers can be used for irrigation or industrial or domestic purposes. But in a certain period one cannot consume more water than is available. The blue water footprint measures the amount of water available in a certain period that is consumed (i.e. not immediately returned within the same catchment). In this way, it provides a measure of the amount of available blue water consumed by humans. The remainder, the ground- and surface water flows not consumed for human purposes, is left to sustain the ecosystems that depend on the ground- and surface water flows.

The blue water footprint in a process step is calculated as:

$$WF_{proc,blue} = BlueWaterEvaporation + BlueWaterIncorporation + LostReturnflow$$

The last component refers to the part of the return flow that is not available for reuse within the same catchment within the same period of withdrawal, either because it is returned to another catchment (or discharged into the sea) or because it is returned in another period of time. The unit of the blue process water footprint is water volume per unit of time, e.g. per day, month or year. When divided over the quantity of product that stems from the process, the process water footprint can also be expressed in terms of water volume per unit of product.

Each component of the blue process water footprint can be measured. Alternatively, for manufacturing processes, one can rely on databases that contain typical data on consumptive water use per type of manufacturing process. Such databases, however, do hardly exist and generally contain data on water withdrawals, not on consumptive water use. Besides, these databases generally lack the necessary details and contain data on water use per industrial sector (e.g. sugar refineries, textile mills, paper mills, etc.) rather than

per manufacturing process. Two data-rich compendiums are Gleick (1993) and Van der Leeden (1990), but both are US-focused and mainly limited to data on water withdrawals. The best sources for blue water consumption in manufacturing processes are the manufacturers themselves or regional or global branch organisations.

Blue water consumption in agriculture can be measured, but generally one will have to rely on models to estimate irrigation water requirements plus information on whether and when irrigation takes place. Available statistics on irrigation show water withdrawals, not consumptive water use. In Section 3.2.4 we will show in more detail how one can estimate the blue water footprint in crop growth.

In assessing the blue water footprint of a process one may wish to distinguish between different sorts of blue water sources. The most relevant division is between surface water, flowing (renewable) groundwater and fossil groundwater. One can make the distinction by speaking respectively of the blue surface-water footprint, the blue renewable-groundwater footprint and the blue fossil-groundwater footprint (or the light-blue, dark-blue and black water footprint if one really likes the use of the colours). In practice, it is often very difficult to make the distinction because of lacking data, that is why the distinction is often not made.

3.2.2. Green water footprint

The green water footprint is an indicator of the human use of so-called green water. Green water refers to the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Green water can be made productive for crop growth (but not all green water can be taken up by crops, because there will always be evaporation from the soil and because not all periods of the year or areas are suitable for crop growth).

The green water footprint is the volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (products based on crops or wood), where it refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood. The green water footprint in a process step is equal to:

$$WF_{proc,green} = GreenWaterEvaporation + GreenWaterIncorporation$$

The distinction between the blue and green water footprint is important because the hydrological, environmental and social impacts and the economic opportunity costs of surface and groundwater use for production differ distinctively from the impacts and costs of rainwater use (Falkenmark and Rockström, 2004; Hoekstra and Chapagain, 2008).

Green water consumption in agriculture can be measured or estimated with a set of empirical formulas or crop model suitable for estimating evapotranspiration based on input data on climate, soil and crop characteristics. In Section 3.2.4 we will present in more detail how one can estimate the green water footprint in crop growth.

3.2.3. Grey water footprint

The grey water footprint of a process step is an indicator of the degree of freshwater pollution that can be associated with the process step. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on 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 ambient water remains above agreed water quality standards. The grey component of water use, expressed as a dilution water requirement, has been recognised earlier by for example Postel et al. (1996) and Chapagain et al. (2006). We prefer not to speak about 'dilution water requirement' because it has caused some confusion with people who thought that the term implies that we need to dilute pollutants instead of reduce their emission. This is, of course, not the meaning of the concept. The grey water footprint is an indicator of pollution and the less pollution the better. The term 'grey water footprint' was for the first time introduced by Hoekstra and Chapagain (2008). Some recent studies that include quantification of grey water footprints include Van Oel et al. (2009), Dabrowski et al. (2009), Aldaya and Hoekstra (2009), Bulsink et al. (2009) and Gerbens-Leenes and Hoekstra (2009).

The grey water footprint is calculated by dividing the pollutant load (L, in mass/time) by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration c_{max}, in mass/volume) and its natural concentration in the receiving water body (c_{nat}, in mass/volume).

$$WF_{proc,grey} = \frac{L}{c_{max} - c_{nat}}$$

When chemicals are directly released into a surface water body, the load can directly be measured. When a chemical is applied on or put into the soil, like in the case of solid waste or use of fertilisers or pesticides, it may happen that only a fraction seeps into the groundwater or runs off over the surface to a surface water stream. In this case, the pollutant load is the fraction of the total amount of chemicals applied that reaches the ground- or surface water.

The natural concentration in a receiving water body is the concentration in the water body that would occur if there were no human disturbance in the catchment. One may ask why the natural concentration is used as a reference and not the actual concentration in the receiving water body. The reason is that the grey water footprint is an indicator of appropriated assimilation capacity. The assimilation capacity of a receiving water body depends on the difference between the maximum allowable and the natural concentration of a substance. If one would compare the maximum allowable concentration with the actual concentration of a substance, one

would look at the *remaining* assimilation capacity, which is obviously changing all the time, as a function of the actual level of pollution at a certain time.

The critical load (L_{crit}, in mass/time) is the load of pollutants that will fully consume the assimilation capacity of the receiving water body. It can be calculated by multiplying the runoff of the water body (R, in volume/time) by the difference between the maximum acceptable and natural concentration:

$$L_{crit} = R \times (c_{max} - c_{nat})$$

This equation and the one before assume that the decay of the substance is negligible over short time frames, so that a load given at a certain point in time will immediately raise the concentration in a receiving water body correspondingly. When the load into a flowing water body reaches the critical load, the grey water footprint will be equal to the runoff, which means that full runoff is appropriated for waste assimilation.

In the case that pollutants are part of an effluent discharged into a water body, the pollutant load can be calculated as the effluent volume ($Effl$, in volume/time) multiplied by the difference between the concentration of the pollutant in the effluent (c_{effl}, in mass/volume) and its natural concentration in the receiving water body (c_{nat}, in mass/volume). The grey water footprint can then be calculated as follows:

$$WF_{proc,grey} = \frac{L}{c_{max} - c_{nat}} = \frac{Effl \times (c_{effl} - c_{nat})}{c_{max} - c_{nat}}$$

The pollutant load L is thus defined as the load that comes on top of the natural concentration in the receiving water body. How this equation works out under a number of particular cases is discussed in Box 3.3. For human-made substances that naturally do not occur in water, $c_{nat} = 0$, so that:

$$WF_{proc,grey} = \frac{Effl \times c_{effl}}{c_{max}}$$

This equation can also be used when natural concentrations are not known precisely but relatively low. This assumption gives a overestimated grey water footprint when $c_{effl} < c_{max}$ and an underestimate when $c_{effl} > c_{max}$.

For thermal pollution, we can apply a similar approach as for pollution by chemicals. The grey water footprint is now calculated as the difference between the temperature of an effluent flow and the receiving water body (^{o}C) times the effluent volume (volume/time) divided by the maximum acceptable temperature increase (^{o}C).

$$WF_{proc,grey} = \frac{Effl \times \Delta T_{effl}}{\Delta T_{max}} = \frac{Effl \times (T_{effl} - T_{nat})}{T_{max} - T_{nat}}$$

Box 3.3. *Interpretation of the grey water footprint definition.*

- When $c_{effl} = c_{nat}$ the associated grey water footprint is nil. This can easily be understood, because the concentration of the receiving water body will remain unchanged.

- When $c_{effl} = c_{max}$ the grey water footprint is equal to the effluent volume. One may ask why there is a grey water footprint larger than zero when the effluent concentration meets the ambient water quality standard. The answer is that some of the capacity to assimilate pollutants has been consumed. Due to the effluent, the concentration of the chemical in the receiving water body has moved from c_{nat} in the direction of c_{max}. In the extreme case that all water in a river is withdrawn and returned as effluent with a concentration equal to c_{max}, then the full assimilation capacity of the river has been consumed, so the grey water footprint would be equal to the total river runoff.

- When $c_{effl} < c_{nat}$ the calculated grey water footprint will be negative. This can be understood because the effluent is cleaner than the natural water conditions. 'Cleaning' when the river is actually still under natural conditions does not make much sense, because some natural concentration is apparently natural; under these conditions it is recommended to put the grey water footprint at zero. If, however, other activities have brought the natural concentration up already, cleaning actually contributes to bringing the ambient water quality back in the direction of natural conditions, so one can leave the negative footprint value as it is.

- When $c_{max} = 0$ (the case of a complete ban of a highly persistent or toxic pollutant), any effluent with a concentration larger than zero will create an infinitely large grey water footprint. This infiniteness corresponds to the absolute ban: absolutely unacceptable means the footprint goes sky high.

- The case of $c_{max} = c_{nat}$ would create an infinitely large grey water footprint as well, but this case will not occur, because setting standards equal to the natural concentration does not make sense and will normally not happen.

- When the calculated grey water footprint is smaller than the existing river flow or groundwater flow, then there is still sufficient water to dilute the pollutants to a concentration below the standard. When the calculated grey water footprint is precisely equal to the ambient water flow, then the resultant concentration will be exactly at the standard. A grey water footprint larger than zero does not automatically imply that ambient water quality standards are violated; it just shows that part of the assimilation capacity has been consumed already.

- When the effluent contains a very high load of chemicals it may happen that the calculated grey water footprint exceeds the existing river flow or groundwater flow. In this case, pollution goes beyond the assimilation capacity of the receiving water body. The fact that the grey water footprint can be larger than the existing water flow illustrates that the grey water footprint does not show 'the polluted water volume' (because one would not be able to pollute a larger volume than the existing one). Instead, the grey water footprint is an indicator of the severity of water pollution, expressed in terms of the freshwater volume required to assimilate the existing load of pollutants.

The maximum acceptable temperature increase depends on the type of water and local conditions. If no local guideline is available, we recommend reckoning with a default value of 3 ^{o}C (EU, 2006).

Daily values for the grey water footprint can be added over the year to get annual values. When a waste flow concerns more than one form of pollution, as is generally the case, the grey water footprint is determined by the pollutant that is most critical, i.e. the one that is associated with the largest pollutant-specific grey water footprint. For the purpose of finding an overall indicator of water pollution, the grey water footprint based on the critical substance is sufficient. If one is interested in the pollutant-specific grey water footprints, one can of course report those values separately. For formulating response measures targeted at specific pollutants, this is of course very relevant. For the overall picture of pollution, however, showing the grey water footprint for the critical substance is good enough.

Grey water footprint calculations are carried out using ambient water quality standards for the receiving freshwater body, i.e. standards with respect to maximum allowable concentrations. The reason is that the grey

water footprint aims to show the required ambient water volume to assimilate chemicals. Ambient water quality standards are a specific category of water quality standards. Other sorts of standards are for instance drinking water quality standards, irrigation quality standards and emission (or effluent) standards. One should take care using ambient water quality standards. For one particular substance, the ambient water quality standard may vary from one to another water body. Besides, the natural concentration may vary from place to place. As a result, a certain pollutant load can result in another grey water footprint in one place compared to another place. This is reasonable, because the effect of a certain load will indeed be different depending on the difference between the maximum allowable and the natural concentration.

Although ambient water quality standards often exist in national or state legislation or have to be formulated by catchment and/or water body in the framework of national legislation or by regional agreement (like in the European Water Framework Directive – see EU, 2000), they do not exist for all substances and for all places. Most important is of course to specify which water quality standards have been used in preparing a grey water footprint account.

3.2.4. Calculation of the green, blue and grey water footprint of growing a crop or tree

Many products contain ingredients from agriculture or forestry. Crops are used for food, feed, fibre, fuel, oils, soaps, cosmetics, etc. Wood from trees and shrubs is used for timber, paper and fuel as well. Since the agricultural and forestry sectors are major water consuming sectors, products that involve agriculture or forestry in their production system will often have a significant water footprint. For all those products it is relevant to particularly look into the water footprint of the process of growing the crop or tree. This section discusses the details of assessing the process water footprint of growing crops or trees. The method is applicable to both annual and perennial crops, where trees can be considered a perennial crop. In the following, the term 'crop' is used in a broad sense, thus also including 'trees' grown for the wood.

The total water footprint of the process of growing crops or trees (WF_{proc}) is the sum of the green, blue and grey components:

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

We will express all process water footprints in this section per unit of product, viz. in water volume per mass. Usually we express process water footprints in agriculture or forestry as m^3/ton, which is equivalent to litre/kg.

The green component in the process water footprint of growing a crop or tree ($WF_{proc,green}$, 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 ($WF_{proc,blue}$, m^3/ton) is calculated in a similar way:

$$WF_{proc,green} = \frac{CWU_{green}}{Y}$$

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y}$$

Yields for annual crops can be taken as given in yield statistics. In the case of perennial crops, one should consider the average yield over the full life span of the crop. In this way one will account for the fact that the yield in the initial year of planting is low or zero, that yields are highest after some years and that yields often go down at the end of the life span of a perennial crop.

The grey component in the water footprint of growing a crop or tree ($WF_{proc,grey}$, m^3/ton) is calculated as the chemical application rate per hectare (AR, kg/ha) times the leaching 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).

$$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{max} - c_{nat})}{Y}$$

The pollutants generally consist of fertilizers (nitrogen, phosphorus, etc.), 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 where above calculation yields the highest water volume.

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:

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green}$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue}$$

in which ET_{green} represents green water evapotranspiration and ET_{blue} blue water evapotranspiration. The factor 10 is meant to convert water depths in mm 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* stands for length of growing period in days). Since different crop varieties can have substantial differences in the length of the growing period, this factor can significantly influence the calculated crop water use. For permanent (perennial) crops and production forest, one should account for the evapotranspiration throughout the year. Besides, in order to account for differences in evapotranspiration over the full life span of a permanent crop or tree, one should look at the annual average of evapotranspiration over the full life span of the crop or tree. Suppose, for example, that a

certain perennial crop has a lifespan of twenty years, while it gives a yield only from the sixth year on. In this case, the crop water use over the twenty years needs to be divided over the total yield over the fifteen years of production. The 'green' crop water use represents the total rainwater evaporated from the field during the growing period; the 'blue' crop water use represents the total irrigation water evaporated from the field.

Evapotranspiration from a field can be either measured or estimated by means of a model based on empirical formulas. Measuring 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 input. There are many alternative ways to model ET and crop growth. One of the models frequently used is the EPIC model (Williams et al., 1989; Williams, 1995), also available in grid-based form (Liu et al., 2007). Another model is the CROPWAT model developed by the Food and Agriculture Organization of the United Nations (FAO, 2009b), which is based on the method described in Allen et al. (1998). Without the intention to exclude good alternative models, we recommend to use the CROPWAT model because of its wide application, online availability, good documentation and embedding in FAO practice.

The CROPWAT model offers two different options to calculate evapotranspiration: the 'crop water requirement option' (assuming optimal conditions) and the 'irrigation schedule option' (including the possibility to specify actual irrigation supply in time). We recommend to apply the second option whenever possible, because it is applicable for both optimal and non-optimal growing conditions and because it is more accurate (because the underlying model includes a dynamic soil water balance). A comprehensive manual for the practical use of the CROPWAT program is available online (FAO, 2009b). Box 3.4 summarises how to use the 'crop water requirement option' to estimate green and blue water evapotranspiration under optimal conditions; Box 3.5 summarises the 'irrigation schedule option' that can be applied for all conditions. A practical example of the calculation of the process water footprint of growing a crop is given in Appendix I.

Estimating the green, blue and grey water footprints of growing a crop requires a large number of data (Box 3.6). In general it is always preferable to find local data pertaining to the crop field location. In many cases it is too laborious to collect location-specific data given the purpose of the assessment. If the purpose of the assessment allows a rough estimate, one can decide to work with data from nearby locations or with regional or national averages that may be more easily available.

In the above calculations, we have not yet accounted for the green and blue water incorporated into the harvested crop. One can find that component of the water footprint by simply looking at the water fraction of the harvested crop. For fruits this is typically in the range of 80-90% of the wet mass, for vegetables often 90-95%. The green-blue ratio in the water that is incorporated in the crop can be assumed equal to the ratio of CWU_{green} to CWU_{blue}. However, adding incorporated water to evaporated water will add little to the final water footprint number, because incorporated water is typically in the order of 0.1 percent of the evaporated water and in the order of 1 percent at most.

Box 3.4. *Calculation of green and blue evapotranspiration using the 'CWR option' in the CROPWAT model.*

Green and blue water evapotranspiration during crop growth can be estimated with FAO's CROPWAT model (FAO, 2009b). The model offers two alternative options. The simplest but not the most accurate option is the 'CWR option'. In this option, it is assumed that there are no water limitations to crop growth. The model calculates: (a) crop water requirements (*CWR*) during the full length of the growing period under particular climatic circumstances; (b) effective precipitation over the same period; (c) irrigation requirements.

The crop water requirement is the water needed for evapotranspiration under ideal growth conditions, measured from planting to harvest. 'Ideal conditions' means that adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield. Basically, the crop water requirement is calculated by multiplying the reference crop evapotranspiration (ET_o) by the crop coefficient (K_c): $CWR = K_c \times ET_o$. It is assumed that the crop water requirements are fully met, so that actual crop evapotranspiration (ET_c) will be equal to the crop water requirement: $ET_c = CWR$.

The reference crop evapotranspiration ET_o is the evapotranspiration rate from a reference surface, not short of water. The reference is a hypothetical surface with extensive green grass cover with specific characteristics. The only factors affecting ET_o are climatic parameters. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The actual crop evapotranspiration under ideal conditions differs distinctly from the reference crop evapotranspiration, as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). The crop coefficient varies over the length of the growing period. Values for K_c for different crops over the length of the growing period can be taken from the literature (e.g. Allen et al., 1998). As an alternative, one can calculate K_c as the sum of K_{cb} and K_e, where K_{cb} is the so-called basal crop coefficient and K_e a soil evaporation coefficient. The basal crop coefficient is defined as the ratio of the crop evapotranspiration over the reference evapotranspiration (ET_c/ET_o) when the soil surface is dry but transpiration is occurring at a potential rate, i.e., water is not limiting transpiration. Therefore, $K_{cb} \times ET_o$ represents primarily the transpiration component of ET_c, but it also includes a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation. The soil evaporation coefficient K_e describes the evaporation component of ET_c. When the topsoil is wet, following rain or irrigation, K_e is maximal; when the soil surface is dry, K_e is small and even zero when no water remains near the soil surface for evaporation. Different irrigation techniques wet the soil surface in different degrees. Sprinkler irrigation, for example, wets the soil more than drip irrigation, resulting in a higher value for K_e directly after irrigation. This will translate into a higher value for K_c and thus for ET_c. The CROPWAT model, however, does not allow the specification of K_{cb} and K_e separately; it requires specification of the resultant K_c. Besides, K_c cannot be specified per day but only for three different periods in the growing period, so that the effect of different irrigation techniques can be simulated in CROPWAT only by roughly adjusting K_c as a function of the irrigation technique used. On average, K_c will be higher when irrigation techniques are applied that wet the soil intensively than when techniques are used that do not wet the top soil much.

Effective precipitation (P_{eff}) is the part of the total amount of precipitation that is retained by the soil so that it is potentially available for meeting the water need of the crop. It is often less than the total rainfall because not all rainfall can actually be appropriated by the crop, e.g. due to surface runoff or percolation (Dastane, 1978). There are various ways to estimate effective rainfall based on total rainfall; Smith (1992) recommends the USDA SCS method (the method of the United States Department of Agriculture, Soil Conservation Service). This is one of the alternative methods that the user of CROPWAT can choose from.

The irrigation requirement (*IR*) is calculated as the difference between crop water requirement and effective precipitation. The irrigation requirement is zero if effective rainfall is larger than the crop water requirement. This means: $IR = \max(0, CWR - P_{eff})$. It is assumed that the irrigation requirements are fully met. Green water evapotranspiration (ET_{green}), i.e. evapotranspiration of rainfall, can be equated with the minimum of total crop evapotranspiration (ET_c) and effective rainfall (P_{eff}). Blue water evapotranspiration (ET_{blue}), i.e. field-evapotranspiration of irrigation water, is equal to the total crop evapotranspiration minus effective rainfall (P_{eff}), but zero when effective rainfall exceeds crop evapotranspiration:

$$ET_{green} = \min\left(ET_c, P_{eff}\right)$$

$$ET_{blue} = \max\left(0, ET_c - P_{eff}\right)$$

All water flows are expressed in mm/day or in mm per period of simulation (e.g. ten days)

Box 3.5. Calculation of green and blue evapotranspiration using the 'irrigation schedule option' in the CROPWAT model.

Green and blue water evapotranspiration during crop growth can be estimated with FAO´s CROPWAT model (FAO, 2009b). The model offers two alternative options. The 'irrigation schedule option' is the most advanced one, allowing the specification of the actual irrigation over the growing period. The model does not work with the concept of effective precipitation (as in the case of the 'CWR option', see Box 3.4). Instead, the model includes a soil water balance which keeps track of the soil moisture content over time using a daily time step. For this reason, the model requires input data on soil type. The calculated evapotranspiration is called ET_a, the adjusted crop evapotranspiration, which may be smaller than ET_c due to non-optimal conditions. ET_a is calculated as the crop evapotranspiration under optimal conditions (ET_c) times a water stress coefficient (K_s):

$$ET_a = K_s \times ET_c = K_s \times K_c \times ET_o$$

The stress coefficient K_s describes the effect of water stress on crop transpiration. For soil water limiting conditions, $K_s < 1$; when there is no soil water stress, $K_s = 1$. For the crop coefficient K_c the same can be said as what has been said already in Box 3.4.

Rain-fed conditions can be simulated in the model by choosing to apply no irrigation. In the rain-fed scenario ($irr = 0$), the green water evapotranspiration is equal to the total evapotranspiration as simulated by the model and the blue water evapotranspiration is zero:

$$ET_{green}(irr = 0) = ET_{tot}(irr = 0)$$

$$ET_{blue}(irr = 0) = 0$$

In the irrigation scenario ($irr = 1$) the green water evapotranspiration is equal to the total evapotranspiration as simulated in the rain-fed scenario. To estimate the blue water evapotranspiration, different irrigation timing and application options can be selected depending on the actual irrigation strategy. The default option, 'irrigate at critical depletion' and 'refill soil to field capacity', assumes "optimal" irrigation where the irrigation intervals are at a maximum whilst avoiding any crop stress. The average irrigation application depth per irrigation period is related to the irrigation method practised. Generally, in the case of high frequency irrigation systems, such as micro-irrigation and centre pivot, about 10 mm or less per wetting event are applied. In the case of surface or sprinkler irrigation, irrigation depths are 40 mm or more. After running the model with the selected irrigation options, the blue water evapotranspiration is equal to the total evapotranspiration as simulated in the irrigation scenario minus the green water evapotranspiration:

$$ET_{green}(irr = 1) = ET_{green}(irr = 0)$$

$$ET_{blue}(irr = 1) = ET_{tot}(irr = 1) - ET_{green}(irr = 1)$$

Note that, over the growing period as a whole, blue water evapotranspiration is generally less than the actual irrigation volume applied. The difference refers to irrigation water that percolates to the groundwater or runs off from the field.

Box 3.6. Data sources for the calculation of the water footprint of 'growing a crop'.

- **Climate data**: The calculation should be done using climate data from the nearest and most representative meteorological station(s) located near the crop field considered or within or near the crop-producing region considered. For regions with more than one climate station, one can make calculations for each station and weigh the outputs. The climate database CLIMWAT 2.0 (FAO, 2009a) provides the climatic data needed in the appropriate format required by the CROPWAT 8.0 model. The database does not provide data for specific years, but 30-year averages. Another source is LocClim 1.1 (FAO, 2005), which provides estimates of average climatic conditions at locations for which no observations are available. One can also use grid-based climate databases: Monthly values of major climatic parameters with a spatial resolution of 30 arc minute can be obtained from CRU TS-2.1 through the CGIAR-CSI GeoPortal (Mitchell and Jones, 2005). The US National Climatic Data Centre provides daily climatic data for a large number of stations globally (NCDC, 2009). In addition, FAO provides through its GeoNetwork website long-term average precipitation and reference evapotranspiration with a spatial resolution of 10 arc minute (FAO, 2009g).
- **Crop parameters**: Crop coefficients and cropping pattern (planting and harvesting dates) can best be taken from local data. The crop variety and suitable growing period for a particular type of crop largely depends upon the climate and many other factors such as local customs, traditions, social structure, existing norms and policies. Therefore, the most reliable crop data are the data obtained from local agricultural research stations. Global databases that can be used are: Allen et al. (1998, Tables 11-12), FAO (2009b), USDA (1994). FAO's online Global Information and Early Warning system (GIEWS) provides crop calendars for major crops for developing countries. One can access the zipped crop calendar images for each continent directly from the web (FAO, 2009f).

- **Crop maps**: Crop harvest areas and yields for 175 crops at 5 arc minute grid cell resolution are available from the website of the Land Use and Global Environmental Change research group, Department of Geography, McGill University (Monfreda et al., 2008).

- **Soil maps**: ISRIC-WISE provides a global data set for derived soil properties both at 5 arc minute and 30 arc minute resolution (Batjes, 2006). In addition, the FAO GeoNetwork website provides maximum available soil moisture data at 5 arc minute resolution (FAO, 2009h). When applying the 'irrigation schedule option' in the CROPWAT model, one needs soil data; if no soil data are available we advise to choose 'medium soil' as a default.

- **Irrigation maps**: The Global Map of Irrigation Areas (GMIA) version 4.0.1 (Siebert et al., 2007) with a spatial resolution of 5 arc minute defines areas equipped for irrigation. Irrigation maps for 26 major crops both at 5 and 30 arc minute resolutions can be obtained from University of Frankfurt website (Portmann et al., 2008, 2009). These data also provide rain-fed crop growing areas for the same 26 crops.

- **Fertiliser application rates**: Preferably one uses local data. A useful global databases is FertiStat (FAO, 2009c). IFA (2009) provides annual fertilizer consumption per country. Heffer (2009) provides fertilizer use per crop for major crop types and major countries.

- **Pesticides application rates**: Preferably one uses local data. NASS (2009) provides an online database for the USA with chemical use per crop. CropLife Foundation (2006) provides a database on pesticides use in the USA. Eurostat (2007) gives data for Europe.

- **Leaching fraction**: No databases available. One will have to work with experimental data from field studies and make rough assumptions. One can assume 10% for nitrogen fertilisers, following Chapagain et al. (2006b).

- **Ambient water quality standards**: Preferably use local standards as regulated in legislation. If no ambient water quality standards are available and the water body is to be suitable for drinking, one can decide to apply drinking water standards. See for instance EU (2000) and EPA (2005). A compilation can be found in MacDonald et al. (2000).

- **Natural concentrations** in receiving water bodies: In more or less pristine rivers, one can assume that natural concentrations are equal to the actual concentrations and thus rely on long-term daily or monthly averages as measured in a nearby measuring station. For disturbed rivers, one will have to rely on historical records or model studies. For some parts of the world good studies are available; for the USA see for instance Clark et al. (2000) and Smith et al. (2003). As a reference, a global database on actual (not natural!) concentrations is available through UNEP (2009). When no information is available, assume the natural concentration according to the best estimate or to be zero.

In this section we have looked into the calculation of the water footprint of growing a crop in the field. The blue water footprint calculated here refers to the evapotranspiration of irrigation water from the crop field only. It excludes the evaporation of water from artificial surface water reservoirs built for storing irrigation water and the evaporation of water from transport canals that bring the irrigation water from the place of abstraction to the field. Water storage and transport are two processes that precede the process of growing the crop in the field and have their own water footprint (Figure 3.4). The evaporation losses in these two preceding process steps can be very significant and should ideally be included when one is interested in the product water footprint of the harvested crop.
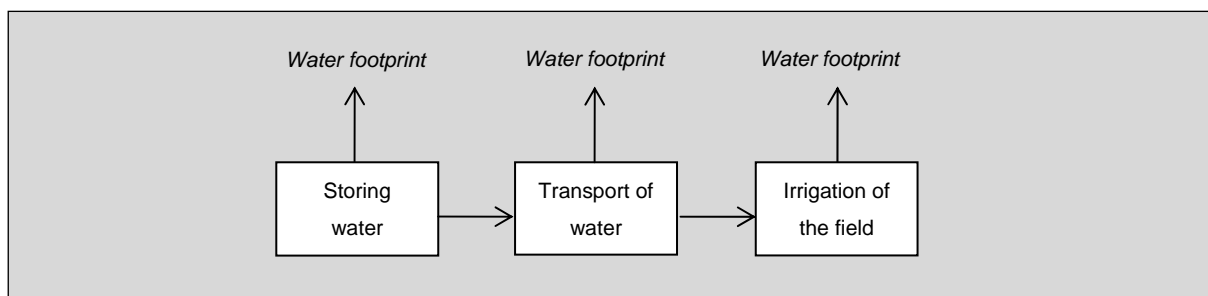

Figure 3.4. *The subsequent processes in irrigation: storing water, transport of water, irrigation on the field. Each process step has its own water footprint.*

3.3. Water footprint of a product

3.3.1. Definition

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[1]. The accounting procedure is similar to all sorts of products, be it products derived from the agricultural, industrial or service sector. The water footprint of a product breaks down into a green, blue and grey component. An alternative term for the water footprint of a product is its 'virtual-water content', but the meaning of the latter term is narrower (Box 3.7).

Box 3.7. *Terminology: water footprint, virtual-water content, embedded water.*

The 'water footprint' of a product is similar to what in other publications has been called alternatively the 'virtual-water content' of the product or the product's embedded, embodied, exogenous or shadow water (Hoekstra and Chapagain, 2008). The terms virtual-water content and embedded water, however, refer to the water volume embodied in the product alone, while the term 'water footprint' refers not only to the volume, but also to the sort of water that was used (green, blue, grey) and to when and where the water was used. The water footprint of a product is thus a multi-dimensional indicator, whereas 'virtual-water content' or 'embedded water' refer to a volume alone. We recommend to use the term 'water footprint' because of its broader scope. The volume is just one aspect of water use; place and timing of water use and type of water used are as important. Besides, the term water footprint can also be used in a context where we speak about the water footprint of a consumer or producer. It would sound strange to speak about the virtual-water content of a consumer or producer. We use the term 'virtual water' in the context of international (or interregional) virtual-water flows. If a nation (region) exports/imports a product, it exports/imports water in virtual form. In this context one can speak about virtual-water export or import, or more general about virtual-water flows or trade.

In the case of agricultural products, the water footprint is generally expressed in terms of m^3/ton or litres/kg. In many cases, when agricultural products are countable, the water footprint can also be expressed as a water volume per piece. In the case of industrial products, the water footprint can be expressed in terms of m^3/US$ or water volume per piece. Other ways to express a product water footprint are for example water volume / kcal (for food products in the context of diets) or water volume / joule (for electricity or fuels).

3.3.2. Schematisation of the production system into process steps

In order to estimate the water footprint of a product one will have to start understanding the way a product is produced. For that reason 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 growth,

---

[1] It is recognized that water use connected to a product is not limited to its production stage. In the case of many products (e.g. a washing machine) there is some form of water use involved in the use stage of the product. This component of water use, however, is not part of the product water footprint. The water use during product use is included in the water footprint of the consumer of the product. Water use in the reuse, recycle or disposal stage of a product is included in the water footprint of the business or organisation that provides that service and is included in the water footprints of the consumers that benefit from that service.

harvesting, ginning, carding, knitting, bleaching, dying, printing, finishing. Given the fact that many products require multiple inputs, it often happens that multiple process steps precede one next process step. In such a case we will not have a linear chain of process steps, but rather a 'product tree'. A (simplified) example of a product tree is: produce feed and all sorts of other inputs necessary in intensive livestock farming, raise the animals and finally produce meat. Since production systems often produce more than one final product – cows can deliver for instance milk as well as meat and leather – even the metaphor of a product tree is insufficient. In reality production systems are complex networks of linked processes, in many cases even circular.

For estimating the water footprint of a product, one will have to schematise the production system into a limited number of linked process steps. Besides, when one intends to go beyond a very superficial analysis based on global averages, one will have to specify the steps in time and space, which means that one will have to trace the origin of the (inputs of the) product. In the cotton-shirt example above, cotton growth may happen in one place (China), while manufacturing may happen in another place (Malaysia) and consumption in yet another place (Germany). Production circumstances and process characteristics will differ from place to place, so that place of production will influence the size and colour of the water footprint. Besides, in the end one may like to be able to geographically map the water footprint of a final product, so that's another reason to keep track of place.

Schematization of a production system into distinct process steps inevitably requires assumptions and simplifications. Particularly relevant is the truncation problem as already mentioned in Chapter 2. Theoretically, because many production systems contain circular components, one could infinitely keep on tracing back inputs through the network of linked process steps. In practice one will have to stop the analysis at those points where additional work will not add more significant information for the purpose of the analysis.

Production system diagrams for agricultural products can be found for example in FAO (2003) and Chapagain and Hoekstra (2004). For industrial products one can generally relatively easily construct a production system diagram based on publicly available data sources. Better of course is to seek information on which process steps are taken in the actual supply-chain of the product considered. This requires tracing of all product ingredients.

3.3.3. Calculation of a product water footprint

The water footprint of a product can be calculated in two alternative ways: with the chain-summation approach or the step-wise accumulative approach, both of which give the same result at the end.

The chain-summation approach
This approach is simpler than the one that will be discussed next, but can only be applied in the case where a production system produces only one output product (Figure 3.5). 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.
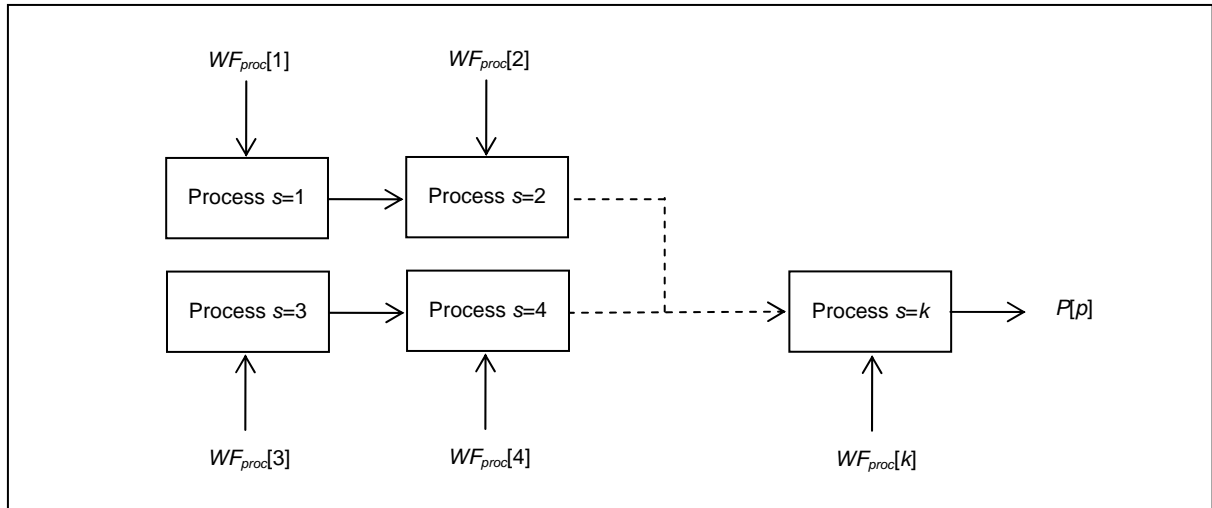
Figure 3.5. *Schematisation of the production system to produce product p into k process steps. Some steps are in series, others are parallel. The water footprint of output product p is calculated as the sum of the process water footprints of the processes that constitute the production system. Note: this simplified scheme presupposes that p is the only output product following from the production system.*

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

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

in which $WF_{proc}[s]$ 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 step-wise 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. In this case we can get the water footprint of the output product by simply summing the water footprints of the input products and add 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 (Figure 3.6). 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 result in *z* output products. We number the output products from *p*=1 to *z*.
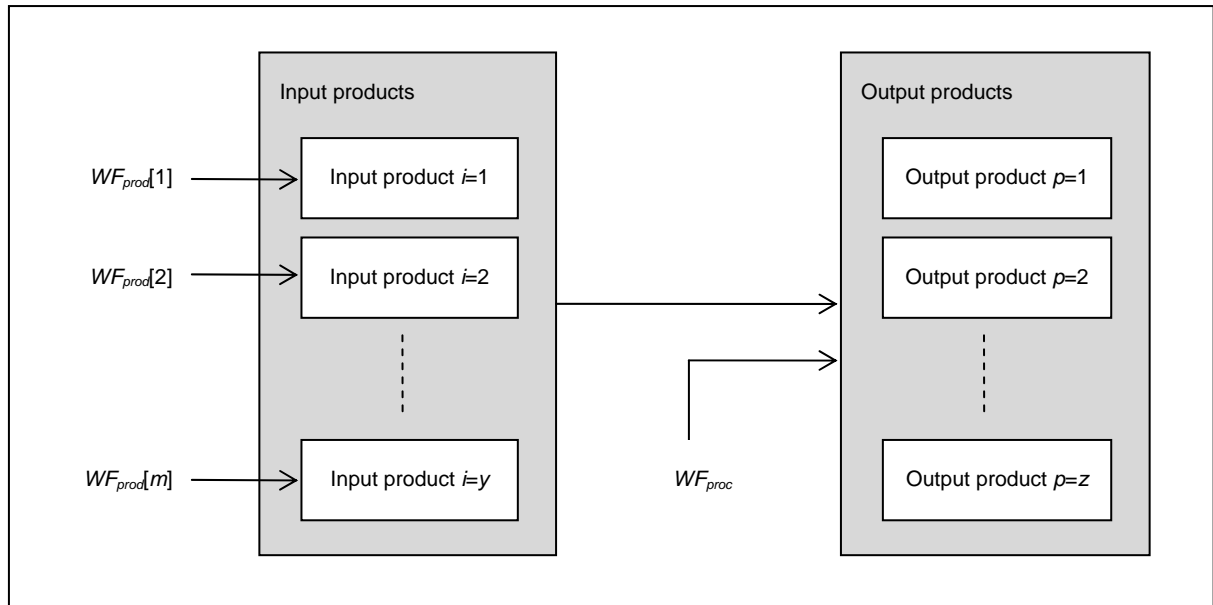
Figure 3.6. *Schematisation of the last process step in the production system to produce product p. The water footprint of output product p is calculated based on the water footprints of the input products and the process water footprint when processing the inputs into the outputs.*

If during processing there is some water use involved, 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:

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

in which $WF_{prod}[p]$ 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'. Both will be defined below.

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):

$$f_p[p,i] = \frac{w[p]}{w[i]}$$

34

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 outputs products ($p=1$ to z) obtained from the input products:

$$f_v[p] = \frac{price[p] \times w[p]}{\sum\limits_{p=1}^{z} \left(price[p] \times w[p] \right)}$$

in which $price[p]$ 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. Of course one can best take the real economic value.

Note that in a simple case, where we process just one input product into one output product, the calculation of the water footprint of the output product becomes rather simple:

$$WF_{prod}[p] = WF_{proc}[p] + \frac{WF_{prod}[i]}{f_p[p,i]}$$

In order to calculate the water footprint of the final product in a production system, one can best start calculating the water footprints of the most original resources (where the supply chain starts) and then calculate, step-by-step, the water footprints of the intermediate products, until one can calculate the water footprint of the final product. The first step is always to obtain the water footprints of the input products and the water used to process them into the output product. The total of these components is then distributed over the various output products, based on their product fraction and value fraction.

A practical example of the calculation of the water footprint of a crop product is given in Appendix II.

Product fractions can best be taken from the literature available for a specific production process. Product fractions are often in a rather narrow range, but sometimes the amount of output product per unit of input product really depends on the precise process applied. In that case it is important to know which type of process is being applied in the case considered. For crop and livestock products, product fractions can be found in FAO (2003) and in Chapagain and Hoekstra (2004, see volume 2). Value fractions fluctuate over the years depending on price developments. In order to avoid a large effect of the price fluctuation on the outcome of the water footprint calculations, we recommend estimating value fractions based on the average price over at least a five-year period. Value fractions for a large range of crop and livestock products are reported in Chapagain and Hoekstra (2004). We recommend, however, to look first for data that link to the actual case considered before taking default values from literature. The process water footprint in a certain process step may vary depending on the type of method applied (e.g. wet or dry milling, dry or wet cleaning, closed cooling system or open

cooling system with water evaporating). For many processes, one can find some estimates on water withdrawals in literature, but not on consumptive water use. General data on pollution per process are also scarce; they will strongly vary from place to place as well, so using general estimates would be very crude. One will have to look for the data at the source, i.e. the producers and factories.

3.4. Water footprint of a consumer or group of consumers

3.4.1. Definition

The water footprint of a consumer is defined as the total volume of freshwater consumed and polluted for the production of the goods and services consumed by the consumer. The water footprint of a group of consumers is equal to the sum of the water footprints of the individual consumers.

3.4.2. Calculation

The water footprint of a consumer (WF_{cons}) is calculated by adding the direct water footprint of the individual and his/her indirect water footprint:

$$WF_{cons} = WF_{cons,dir} + WF_{cons,indir}$$

The direct water footprint refers to the water consumption and pollution that is related to water use at home or in the garden. The indirect water footprint refers to the water consumption and pollution of water that can be associated with the production of the goods and services consumed by the consumer. It refers to the water that was used to produce for example the food, clothes, paper, energy and industrial goods consumed. The indirect water use is calculated by multiplying all products consumed by their respective product water footprint:

$$WF_{cons,indir} = \sum_{p} \left(C[p] \times WF^*_{prod}[p] \right)$$

$C[p]$ is consumption of product p (product units/time) and $WF^*_{prod}[p]$ the water footprint of this product (water volume/product unit). The set of products considered refers to the full range of final consumer goods and services. The water footprint of a product is defined and calculated as described in the previous section.

The total volume of p consumed will generally originate from different places x. The average water footprint of a product p consumed is calculated as:

$$WF^*_{prod}[p] = \frac{\sum_{x} \left(C[x,p] \times WF_{prod}[x,p] \right)}{\sum_{x} C[x,p]}$$

where $C[x,p]$ is consumption of product p from origin x (product units/time) and $WF_{prod}[x,p]$ the water footprint of product p from origin x (water volume/product unit). Depending on the preferred level of detail of analysis, one can trace the origin of the products consumed with more or less precision. If one cannot or does not want to trace the origins of the products consumed, one will have to rely on either global or national average estimates of the water footprints of the products consumed. If, however, one is prepared to trace the origin of products, one can estimate the product water footprints with a high level of spatial detail (see the alternative levels of spatiotemporal explication in water footprint accounting as described in Chapter 1). Preferably the consumer knows per product how much he or she consumes from various origins. If the consumer does not know that, one can assume that the variation in origin equals the variation in origin as available on the national market for that product. The value of $WF^*_{prod}[p]$ can then be calculated with the formula as will be introduced in Section 3.6.3.

The water footprints of final private goods and services are exclusively allocated to the consumer of the private good. The water footprints of public or shared goods and services are allocated to consumers based on the share that each individual consumer takes.

3.5. Water footprint within a geographically delineated area (e.g. province, nation, river basin)

3.5.1. Definition

The water footprint within an area is defined as the total freshwater consumption and pollution within the boundaries of the area. It is crucial to clearly define the boundaries of the area considered. The area can be a catchment area, a river basin, a province, state or nation or any other hydrological or administrative spatial unit.

3.5.2. Calculation

The water footprint within a geographically delineated area (WF_{area}) is calculated as the sum of the process water footprints of all water using processes in the area:

$$WF_{area} = \sum_q WF_{proc}[q]$$

where $WF_{proc}[q]$ refers to the water footprint of a process q within the geographically delineated area. The equation sums over all water-consuming or polluting processes taking place in the area.

From the perspective of water resources protection within a certain area – particularly when the area is water-scarce – it is interesting to know how much water is used in the area to produce export products and how much water is imported in virtual form (in the form of water-intensive products) so that they do not need to be produced within the area. In other words, it is interesting to know the 'virtual-water balance' of an area. The virtual-water balance of a geographically delineated area over a certain time period is defined as the net import

of virtual water over this period ($V_{i,net}$), which is equal to the gross import of virtual water (V_i) minus the gross export (V_e):

$$V_{i,net} = V_i - V_e$$

A positive virtual-water balance implies net inflow of virtual water to the area from other areas. A negative balance means net outflow of virtual water. The gross virtual-water import is interesting in the sense that importing virtual water saves water within the area considered. The gross virtual-water export is interesting in the sense that it refers to a water footprint in the area related to consumption by people living outside the area. Virtual-water imports and exports can be calculated following the same approach as specifically discussed for the case of nations in Section 3.6.3.

3.6. Water footprint within a nation and water footprint of national consumption

3.6.1. The national water footprint accounting scheme

Traditional national water use accounts only refer to the water withdrawal within a country. They do not distinguish between water use for making products for domestic consumption and water use for producing export products. They also exclude data on water use outside the country to support national consumption. In order to support a broader sort of analysis and better inform decision making, the national water use accounts need to be extended. Figure 3.7 shows a visual representation of the national water footprint accounting scheme as was introduced by Hoekstra and Chapagain (2008).

The water footprint of the consumers in a nation ($WF_{cons,nat}$) has two components: the internal water footprint and the external water footprint.

$$WF_{cons,nat} = WF_{cons,nat,int} + WF_{cons,nat,ext}$$

The internal water footprint of national consumption ($WF_{cons,nat,int}$) is defined as the use of domestic water resources to produce goods and services consumed by the national population. It is the sum of the water footprint within the nation ($WF_{area,nat}$) minus the volume of virtual-water export to other nations insofar as related to the export of products produced with domestic water resources ($V_{e,d}$):

$$WF_{cons,nat,int} = WF_{area,nat} - V_{e,d}$$

The external water footprint of national consumption ($WF_{cons,nat,ext}$) is defined as the volume of water resources used in other nations to produce goods and services consumed by the population in the nation considered. It is equal to the virtual-water import into the nation (V_i) minus the volume of virtual-water export to other nations as a result of re-export of imported products ($V_{e,r}$):

38

$$WF_{cons,nat,ext} = V_i - V_{e,r}$$

The virtual-water export (V_e) from a nation consists of exported water of domestic origin ($V_{e,d}$) and re-exported water of foreign origin ($V_{e,r}$):

$$V_e = V_{e,d} + V_{e,r}$$

The virtual-water import into a nation will partly be consumed, thus constituting the external water footprint of national consumption ($WF_{cons,nat,ext}$), and partly be re-exported ($V_{e,r}$):

$$V_i = WF_{cons,nat,ext} + V_{e,r}$$

The sum of V_i and $WF_{area,nat}$ is equal to the sum of V_e and $WF_{cons,nat}$. This sum is called the virtual-water budget (V_b) of a nation.

$$V_b = V_i + WF_{area,nat}$$
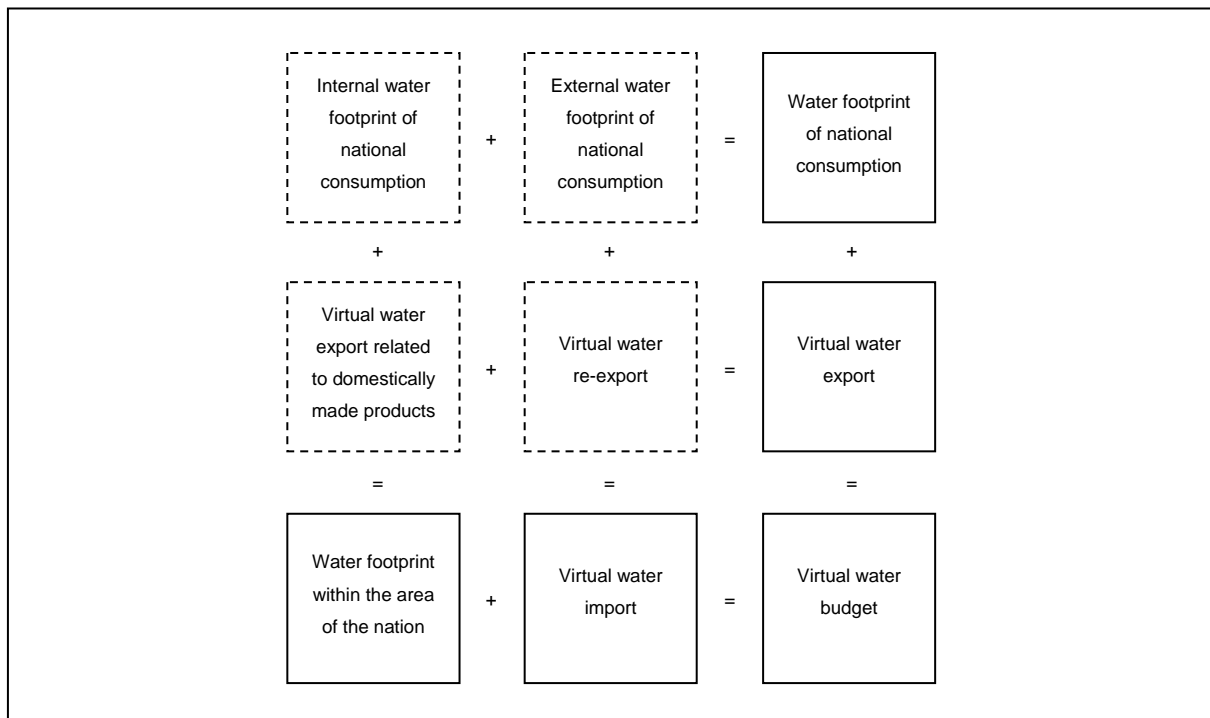$$= V_e + WF_{cons,nat}$$

Figure 3.7. *The national water footprint accounting scheme. The accounting scheme shows the various balances that hold for the water footprint related to national consumption ($WF_{cons,nat}$), the water footprint within the area of the nation ($WF_{area,nat}$), the total virtual-water export (V_e) and the total virtual-water import (V_i).*

3.6.2. Calculation of the water footprint within a nation

The water footprint within a nation ($WF_{area,nat}$, volume/time) is defined as the total freshwater volume consumed or polluted within the territory of the nation. It can be calculated following the method described in Section 3.5:

$$WF_{area,nat} = \sum_q WF_{proc}[q]$$

where $WF_{proc}[q]$ refers to the water footprint of process q within the nation that consumes or pollutes water. The equation sums over all water consuming or polluting processes taking place in the nation. Process water footprints are expressed here in volume/time.

3.6.3. Calculation of the water footprint of national consumption

The water footprint of national consumption ($WF_{cons,nat}$) can be calculated through two alternative approaches: the top-down and the bottom-up approach.

Top-down approach

In the top-down approach, the water footprint of national consumption ($WF_{cons,nat}$, volume/time) is calculated as the water footprint within the nation ($WF_{area,nat}$) plus the virtual-water import (V_i) minus the virtual-water export (V_e):

$$WF_{cons,nat} = WF_{area,nat} + V_i - V_e$$

The gross virtual-water import is calculated as:

$$V_i = \sum_{n_e} \sum_p \left(T_i[n_e, p] \times WF_{prod}[n_e, p] \right)$$

in which $T_i[n_e,p]$ represents the imported quantity of product p from exporting nation n_e (product units/time) and $WF_{prod}[n_e,p]$ the water footprint of product p as in the exporting nation n_e (volume/product unit). If further details are not available, one can assume that a product is produced in the exporting country. One can thus take the average product water footprint as in the exporting country. If one knows the location of origin within the exporting country, one can take the location-specific product water footprint. When a product is imported from a country that does not produce the product and when further information about the real origin is lacking, one can assume the global average product water footprint for that import flow. Ideally, for each product import one takes the product water footprint as measured along the actual supply chain of the product, but in practice this is possibly doable on a case-by-case basis (as shown by Chapagain and Orr (2008) in a study of UK's water footprint), but not in generic sense for all imports into a country. Obviously, one needs to specify the specific assumptions taken in this respect.

The gross virtual-water export is calculated as:

$$V_e = \sum_p T_e[p] \times WF^*_{prod}[p]$$

in which $T_e[p]$ represents the quantity of product p exported from the nation (product units/time) and $WF^*_{prod}[p]$ the average water footprint of the exported product p (volume/product unit). The latter is estimated as:

$$WF^*_{prod}[p] = \frac{P[p] \times WF_{prod}[p] + \sum_{n_e}\left(T_i[n_e,p] \times WF_{prod}[n_e,p]\right)}{P[p] + \sum_{n_e} T_i[n_e,p]}$$

in which $P[p]$ represents the production quantity of product p in the nation, $T_i[n_e,p]$ the imported quantity of product p from exporting nation n_e, $WF_{prod}[p]$ the water footprint of product p when produced in the nation considered and $WF_{prod}[n_e,p]$ the water footprint of product p as in the exporting nation n_e. The assumption made here is that export originates from domestic production and imports according to their relative volumes.

Bottom-up approach

The bottom-up approach is based on the method of calculating the water footprint of a group of consumers (Section 3.4). The group of consumers consists of the inhabitants of a nation. The water footprint of national consumption is calculated by adding the direct and indirect water footprints of consumers within the nation:

$$WF_{cons,nat} = WF_{cons,nat,dir} + WF_{cons,nat,indir}$$

The direct water footprint refers to consumption and pollution of water due to water use by consumers at home or in the garden. The indirect water footprint of consumers refers to the water use by others to make the goods and services consumed. It refers to the water that was used to produce for example the food, clothes, paper, energy and industrial goods consumed. The indirect water footprint is calculated by multiplying all products consumed by the inhabitants of the nation by their respective product water footprint:

$$WF_{cons,nat,indir} = \sum_p \left(C[p] \times WF^*_{prod}[p]\right)$$

$C[p]$ is consumption of product p by consumers within the nation (product units/time) and $WF^*_{prod}[p]$ the water footprint of this product (volume/product unit). The set of products considered refers to the full range of final consumer goods and services. The volume of p consumed in a nation will generally partly originate from the nation itself and partly from other nations. The average water footprint of a product p consumed in a nation is estimated by applying the same assumption that was used in the top-down approach:

$$WF_{prod}^{*}[p] = \frac{P[p] \times WF_{prod}[p] + \sum_{n_e}\left(T_i[n_e, p] \times WF_{prod}[n_e, p]\right)}{P[p] + \sum_{n_e} T_i[n_e, p]}$$

The assumption is that consumption originates from domestic production and imports according to their relative volumes.

The bottom-up versus the top-down approach

The bottom-up and top-down calculations theoretically result in the same figure, provided that there is no product stock change over a year. The top-down calculation can theoretically give a slightly higher (lower) figure if the stocks of water-intensive products increase (decrease) over the year. The reason is that the top-down approach presupposes a balance: $WF_{area,nat}$ plus V_i becomes $WF_{cons,nat}$ plus V_e. This is an approximation only, because, to be more precise: $WF_{area,nat}$ plus V_i becomes $WF_{cons,nat}$ plus V_e plus virtual-water stock increase. Another drawback of the top-down approach is that there can be delays between the moment of water use for production and the moment of trade. For instance in the case of trade in livestock products this may happen: beef or leather products traded in one year originate from livestock raised and fed in previous years. Part of the water virtually embedded in beef or leather refers to water that was used to grow feed crops in previous years. As a result of this, the balance presumed in the top-down approach will hold over a period of a few years, but not necessarily over a single year.

Next to theoretical differences between the two approaches, differences can result from the use of different types of data as inputs of the calculations. The bottom-up approach depends on the quality of consumption data, while the top-down-approach relies on the quality of trade data. When the different databases are not consistent with one another, the results of both approaches will differ. In one particular type of case the outcome of the top-down can be very vulnerable to relatively small errors in the input data. This happens when the import and export of a country are large relative to its domestic production, which is typical for relatively small nations specialised in trade. This has been shown in a case study for the Netherlands (Van Oel et al., 2009). In this case, the water footprint of national consumption calculated with the top-down approach, will be sensitive to the import and export data used. Relative small errors in the estimates of virtual-water import and export translate into a relatively large error in the water footprint estimate. In such a case, the bottom-up approach will yield a more reliable estimate than the top-down approach. In nations where trade is relatively small compared to domestic production, the reliability of the outcomes of both approaches will depend on the relative quality of the databases used for each approach.

External water footprint of national consumption

With either the top-down or bottom-up approach one can calculate the total water footprint of national consumption ($WF_{cons,nat}$). With the top-down approach one can calculate the virtual-water import into a country (V_i). Earlier, in Section 3.6.2, we have seen how one can calculate the water footprint within a nation ($WF_{area,nat}$). Based on these data, the external water footprint of national consumption ($WF_{cons,nat,ext}$) can be calculated as:

$$WF_{cons,nat,ext} = \frac{WF_{cons,nat}}{WF_{area,nat} + V_i} \times V_i$$

This formula can be applied separately for the category of agricultural products (crop and livestock products) and for the category of the industrial products. The formula says that only a fraction of the gross virtual-water import can be said to be the external water footprint of national consumption and that this fraction is equal to the portion of the virtual water budget (sum of water footprint within the nation and virtual-water import) that is to be attributed to national consumption[2]. The other portion of the virtual water budget is exported and is therefore not part of the water footprint of national consumption.

The external water footprint of national consumption can be estimated by export nation n_e and product p by assuming that the national ratio between the external water footprint and the total virtual-water import applies to all partner nations and imported products[3]:

$$WF_{cons,nat,ext}[n_e, p] = \frac{WF_{cons,nat,ext}}{V_i} \times V_i[n_e, p]$$

It happens that products are imported from nations in which they are not produced. For those products one will have to trace the origin country further back. For some product groups, world production is concentrated in specific regions. For these products one can roughly estimate the ultimate place of origin based on world production data. This means that one distributes the water footprint in a non-producing nation over producing nations according to the distribution of the world production.

3.6.4. Water savings related to trade

The national water saving S_n (volume/time) of a nation as a result of trade in product p is defined as:

$$S_n[p] = (T_i[p] - T_e[p]) \times WF_{prod}[p]$$

where $WF_{prod}[p]$ is the water footprint (volume/product unit) of product p in the nation considered, $T_i[p]$ the volume of product p imported (product units/time) and $T_e[p]$ the volume of the product exported (product units/time). Obviously, S_n can have a negative sign, which means a net water loss instead of a saving.

---

[2] This assumption implies that $\dfrac{WF_{cons,nat,ext}}{V_{e,r}} = \dfrac{WF_{cons,nat,int}}{V_{e,d}} = \dfrac{WF_{cons,nat}}{V_e}$ and that $\dfrac{WF_{cons,nat,ext}}{WF_{cons,nat,int}} = \dfrac{V_{e,r}}{V_{e,d}} = \dfrac{V_i}{WF_{area,nat}}$.

[3] One should make an exception for product categories for which re-export is a substantial part of import. The national ratio between $WF_{cons,nat,ext}$ and V_i is not a good assumption here. Instead, one could apply a specific ratio of $WF_{cons,nat,ext}$ to V_i valid to the product category considered.

The global water saving S_g (volume/time) through the trade in product p from an exporting nation n_e to an importing nation n_i, is:

$$S_g\left[n_e,n_i,p\right]=T\left[n_e,n_i,p\right]\times\left(WF_{prod}\left[n_i,p\right]-WF_{prod}\left[n_e,p\right]\right)$$

where T is the volume of trade in p (products units/time) between the two nations. The global saving is thus obtained as the difference between the water productivities of the trading partners. When in a particular case the importing nation is not able to produce the product domestically, we recommend to take the difference between the global average water footprint of the product and the water footprint in the exporting nation.

The total global water saving can be obtained by summing up the global savings of all international trade flows. By definition, the total global water saving is equal to the sum of the national savings of all nations.

3.6.5. National water dependency versus water self-sufficiency

We define the virtual-water import dependency (*WD,* %) of a nation as the ratio of the external to the total water footprint of national consumption:

$$WD=\frac{WF_{cons,nat,ext}}{WF_{cons,nat}}\times100$$

National water self-sufficiency (*WSS,* %) is defined as the internal divided by the total water footprint of national consumption:

$$WSS=\frac{WF_{cons,nat,int}}{WF_{cons,nat}}\times100$$

Both water dependency and water self-sufficiency can best be calculated on an annual basis or as an average over a period of years.

Self-sufficiency is 100% when all the water needed is available and indeed taken from within the own territory. Water self-sufficiency approaches zero if the demands of goods and services in a nation are heavily met with gross virtual-water imports, i.e. the nation has a relatively large external water footprint in comparison to its internal water footprint.

3.7. Water footprint of a business

3.7.1. Definition

The water footprint of a business is defined as the total volume of freshwater that is used directly or indirectly to run and support the business. It consists of two main components. The operational (or direct) water footprint of a business is the volume of freshwater consumed or polluted due to its own operations. The supply-chain (or indirect) water footprint of a business is the volume of freshwater consumed or polluted to produce all the goods and services that form the inputs of production of the business. Instead of the term 'business water footprint' one can also use the term 'corporate water footprint' or 'organisational water footprint'.

The total water footprint of a business can be schematised into components as shown in Figure 3.8. After the distinction between operational and supply-chain water footprint, one can differentiate between the water footprint that can be immediately associated with the product(s) produced by the businesses and the 'overhead water footprint'. The latter is defined as the water footprint pertaining to the general activities for running a business and to the general goods and services consumed by the business. The term 'overhead water footprint' is used to identify water consumption that is necessary for the continued functioning of the business but that does not directly relate to the production of one particular product. In every case, one can distinguish a green, blue and grey water footprint component. Examples of the various components in a business water footprint are given in Table 3.1.
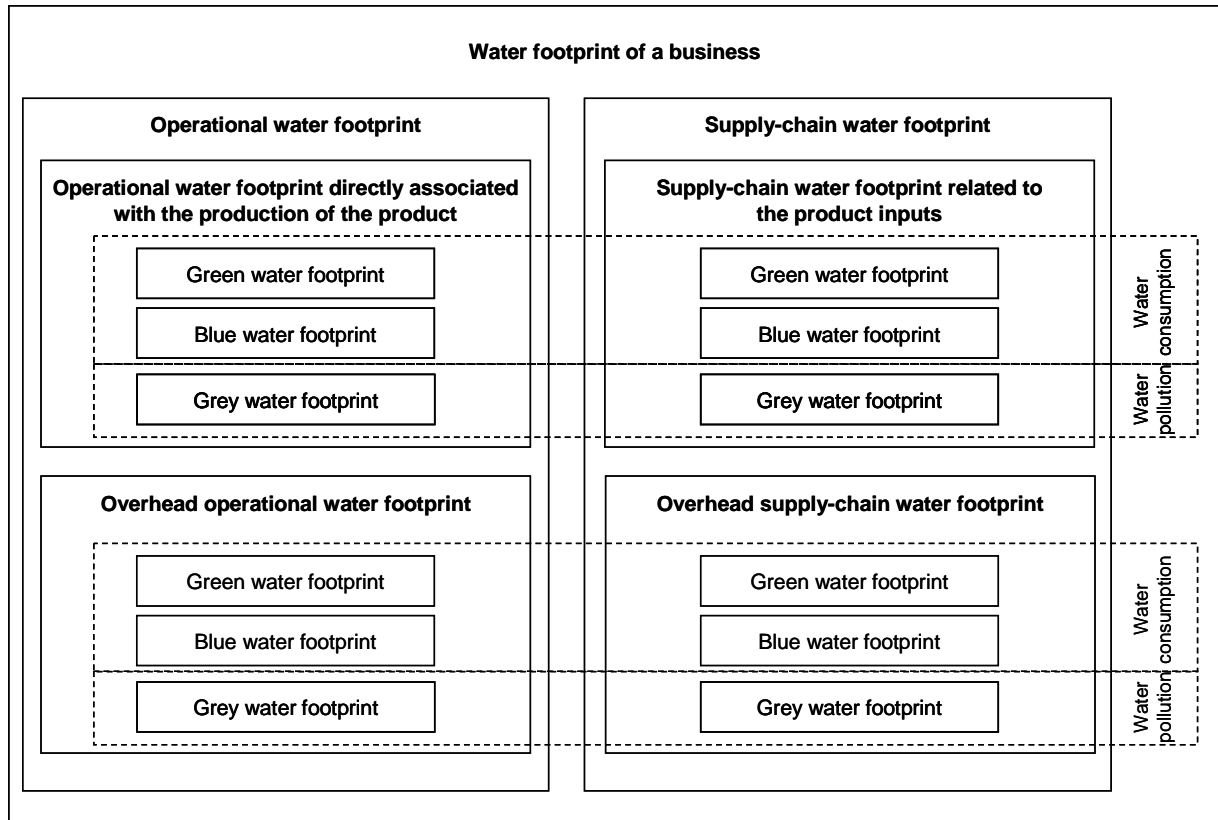

Figure 3.8. *Composition of the water footprint of a business.*

Table 3.1. Examples of the components of a business water footprint.

Operational water footprint		Supply-chain water footprint	
Water footprint directly associated with the production of the business's product(s)	Overhead water footprint	Water footprint directly associated with the production of the business product(s)	Overhead water footprint
• Water incorporated into the product • Water consumed or polluted through a washing process • Water thermally polluted through use for cooling	• Water consumption or pollution related to water use in kitchens, toilets, cleaning, gardening, or washing working clothes.	• Water footprint of product ingredients bought by the company • Water footprint of other items bought by the company for processing their product	• Water footprint of infrastructure (construction materials etc.). • Water footprint of materials and energy for general use (office materials, cars and trucks, fuels, electricity, etc.)

In addition to the operational and supply-chain water footprint, a business may like to distinguish an 'end-use water footprint' of its product. This water footprint refers to the water consumption and pollution by consumers when using the product, e.g. think about the water pollution that results from the use of soaps in the household. The end-use water footprint of a product is strictly spoken not part of the business water footprint or the product water footprint, but part of the consumer's water footprint. Consumers can use products in various ways, so that estimating the 'end-use water footprint' of a product will require assumptions about average usage.

By definition, the 'water footprint of a business' is equal to the 'sum of the water footprints of the business output products'. The 'supply-chain water footprint of a business' is equal to the 'sum of the water footprints of the business input products'. Calculating a business water footprint or calculating the water footprint of the major product(s) produced by a business is about the same thing, but the focus is different. In the calculation of a business water footprint there is a strong focus on making the distinction between an operational (direct) and supply-chain (indirect) water footprint. This is highly relevant from a policy perspective, because a business has direct control over its operational water footprint and indirect influence on its supply-chain water footprint. When calculating a product water footprint there is no distinction between direct and indirect water footprint; one simply considers the process water footprints for all relevant processes within the production system, ignoring how the production system may be owned and operated by different companies. An hybrid between a product and business water footprint account is possible by focussing on the calculation of the water footprint of a particular product – e.g. by looking at just one of many products produced by a business – but making explicit which part of the product's water footprint occurs in the business's own operations and which part in the business's supply chain.

Business water footprint accounting offers a new perspective for developing a well-informed corporate water strategy. This is because the water footprint as an indicator of water use differs from the indicator 'water withdrawal in the own operations' used by most companies thus far. Box 3.8 discusses a few possible implications for companies that start to look at their water footprint.

3.7.2. Choosing the organisational boundaries of the business

A business is conceived here as a coherent entity producing goods and/or services that are supplied to consumers or other businesses. It can be a private company or corporation, but also a governmental or non-governmental organisation. It can refer to various levels of scale, for instance a specific unit or division of a company, an entire company or a whole business sector. In the public sector, one may refer to a unit within a municipality as well as to national government as a whole. The term business can also refer to a consortium or joint-venture of companies or organisations aimed at the delivery of a certain good or service. In fact, the term business can also refer to any project (e.g. construction of a piece of infrastructure) or activity (e.g. the organization of a large sports event). In this way, the term business has been defined so broad that it can refer to all sorts of corporations, organizations, projects and activities. In technical terms, a business is here understood as any coherent entity or activity that transforms a set of inputs into one or more outputs.

In order to be able to assess the water footprint of a business, the business should be clearly delineated. It should be clear what are the boundaries of the business considered. It should be possible to schematise the business into a system that is clearly distinguished from its environment and where inputs and outputs are well known.

Whatever type of company, companies often consist of a number of units. For example, a company can have operations (e.g. factories) at various locations. Or a company may have separate divisions at one location. For the purpose of water footprint accounting, it is often useful to distinguish between different business units. For instance, when a manufacturing company has different factories at different locations, the individual factories are likely to operate under different conditions and derive their inputs from different places. In such a case, it is useful to do water footprint accounting per business unit first and later on aggregate the business unit accounts into an account for the business as a whole.

The business needs to be defined by describing the business units that will be distinguished and specifying the annual inputs and outputs per business unit. Inputs and outputs are described in physical units. Preferably, a

business unit refers to a part of the total business that produces one particular product at one particular spot. When a business runs at different locations, it is thus preferred to schematize the overall business into business units in such a way that individual business units operate at one location. Besides, operations of a business at one particular spot are preferably schematised in different business units each producing its own product. It is most useful to schematise the business based on the various primary products delivered by the business. However, one can also distinguish service units providing only goods or services to primary production units.

As an example, Figure 3.9 shows a business producing output products A, B and C. The business consists of three business units. Unit 1 produces product A. Part of A is delivered to business unit 2, but most is sold to other businesses. Unit 2 produces product B, which is partly sold to another business and partly delivered to unit 3. Unit 3 produces product C, both for delivery to unit 2 and for selling externally. Each unit has an intake of a number of input products derived from companies in a preceding link of the production chain, and a related indirect freshwater input, as well a direct freshwater input. A schema like the one shown in Figure 3.9 can form the basis for calculating a business water footprint, as will be explained in the next section.
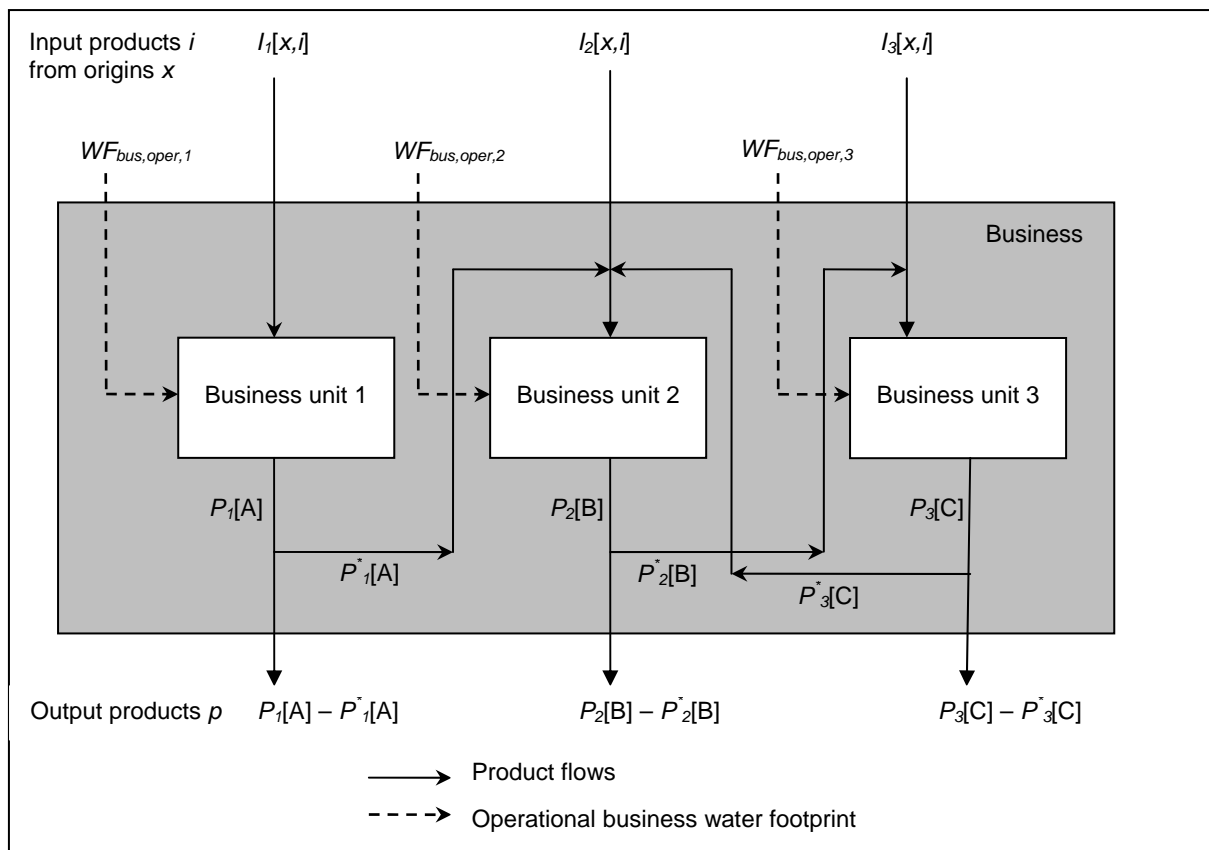
Figure 3.9. *Business that consists of three business units producing products A-C. Product inflow $I_u[x,i]$ refers to the annual volume of input product i from source x into business unit u. Product outflow $P_u[p]$ refers to the annual volume of output product p from business unit u. Product flow $P^*_u[p]$ refers to the part of $P_u[p]$ that goes to another business unit within the same business.*

48

When a business is large and heterogeneous (different locations, different products), it can be attractive to schematise the business into some major business units and each major unit into a number of minor units again. In this way the business can be schematised as a system with subsystems at a number of levels. Later on the water footprint accounts at the lowest level can be aggregated to accounts at the second-lowest level, etcetera, up to the level of the business as a whole.

3.7.3. Calculation of the business water footprint

Below we will show how one can calculate the water footprint of a 'business unit'. In the end of the section, it will be shown how one can calculate the water footprint of a business consisting of a number of business units. The water footprint of a business unit (WF_{bus}, volume/time) is calculated by adding the operational water footprint of the business unit and its supply-chain water footprint:

$$WF_{bus} = WF_{bus,oper} + WF_{bus,sup}$$

Both components consist of a water footprint that can be directly associated with the production of the product in the business unit and an overhead water footprint:

$$WF_{bus,oper} = WF_{bus,oper,inputs} + WF_{bus,oper,overhead}$$
$$WF_{bus,sup} = WF_{bus,sup,inputs} + WF_{bus,sup,overhead}$$

The operational water footprint is equal to the consumptive water use and the water pollution that can be associated with the operations of the business. Following the guidelines provided in Section 3.2, one can simply look at the evaporative flow from the operations, the volume of water incorporated into products and the return flows of water to other catchments than from which water was withdrawn. In addition, one has to consider effluent volumes and concentrations of chemicals therein. The operational overhead water footprint – water consumption and pollution related to general water-using activities in the business unit – can be identified and quantified just like the operational water footprint directly associated with the production process. The overhead water footprint, however, will often serve more than the business unit considered. For example, the overhead of a factory with two production lines will have to be distributed over the two production lines. If one has defined a business unit such that it refers to one of the production lines, one needs to calculate the share of the overhead water footprint that is to be accounted to the one production line. One can do this according to the production values of the two production lines.

The supply-chain water footprint per business unit (volume/time) can be calculated by multiplying the various input-product volumes (data available from the business itself) by their respective product water footprints (data that have to be obtained from suppliers). Supposed that there are different input products *i* originating from different sources *x*, the supply-chain water footprint of a business unit is calculated as:

$$WF_{bus,sup} = \sum_{x}\left(\sum_{i}\left(WF_{prod}[x,i]\times I[x,i]\right)\right)$$

in which $WF_{bus,sup}$ represents the supply-chain water footprint of the business unit (volume/time), $WF_{prod}[x,i]$ the water footprint of input product i from source x (volume/unit of product) and $I[x,i]$ the volume of input product i from source x into the business unit (product units/time).

The product water footprint depends on the source of the product. When the product comes from another business unit within the same business, the value of the product water footprint is known from the own accounting system (see the end of this section). When the product originates from a supplier outside the own business, the value of the product water footprint has to be obtained from the supplier or estimated based on indirect data known about the production characteristics of the supplier. The various product water footprints are composed of three colours (green, blue, grey), which should be accounted separately, so that the resulting supply-chain water footprint of the business unit consists of three colour-components as well.

The water footprint of each specific output product of a business unit is estimated by dividing the business-unit water footprint by the output volume. Allocation of the water footprint over the output products can be done in several ways, for example, according to mass, energy content or economic value. Following what is common in life cycle assessment studies, it is recommended to allocate according to economic value. The product water footprint of output product p from a business unit ($WF_{prod}[p]$, volume/unit of product) can then be calculated as:

$$WF_{prod}[p] = \frac{E[p]}{\sum_{p}E[p]}\times\frac{WF_{bus}}{P[p]}$$

in which $P[p]$ is the volume of output product p from the business unit (product units/time), $E[p]$ the total economic value of output product p (monetary unit/time) and $\sum E[p]$ the total economic value of all output products together (monetary unit/time). If the business unit delivers only one product, the equation is reduced to:

$$WF_{prod}[p] = \frac{WF_{bus}}{P[p]}$$

All above equations are to be applied at the level of a business unit. Suppose that a business has been schematised into a number of business units u, the water footprint of the business as a whole ($WF_{bus,tot}$) is calculated by aggregating the water footprints of its business units. In order to avoid double counting, one has to subtract the virtual-water flows between the various business units within the business:

$$WF_{bus,tot} = \sum_{u}WF_{bus}[u] - \sum_{u}\sum_{p}\left(WF_{prod}[u,p]\times P^{*}[u,p]\right)$$

in which $P^*[u,p]$ stands for the annual volume of output product p from business unit u to another business unit within the same business (product units/time).

4. Water footprint sustainability assessment

4.1. Introduction

Whether the water footprint of a process, product, consumer or producer is sustainable depends on (1) the characteristics of the water footprint (size, timing, location, colour, etc.) and (2) the local conditions in the place(s) where the water footprint is located as well as the wider context in which the water footprint takes place. Sustainability can be analysed from an environmental as well as a social or economic perspective. Furthermore, sustainability can be considered at various scales. At each scale, specific questions can be posed (Table 4.1).

Let us consider for example the case of a blue water footprint related to jatropha production for biodiesel. River water is used for irrigating the plant in certain parts of the year. Let us further focus on *environmental* sustainability. Suppose that some ecologists have studied the so-called 'environmental flow requirements' in the river at the spot where the regular water withdrawal for irrigation takes place. These environmental flow requirements tell that certain monthly water flows are minimally necessary to maintain the ecological characteristics of the river. A first relevant local question is: are environmental flow requirements of the river met at the location where and during the period that the irrigation water is withdrawn from the river? This may be the case at the location of withdrawal, but it may happen that – although locally there is no significant impact – downstream there is an impact due to the aggregated result of various consumptive withdrawals including the withdrawal for jatropha irrigation. Therefore a question at the river-basin level is: does the blue water footprint of jatropha production contribute to the violation of environmental flow requirements somewhere downstream in the river? Suppose that also this is not the case. Then there is still another relevant question. Even though the blue water footprint of jatropha in this case does have neither an immediate local environmental impact nor an indirect downstream environmental impact, one can question whether allocating some of the world's scarce freshwater resources to irrigate jatropha for making biodiesel is a sustainable choice. The world's blue water resources are limited. When we subtract from the total annual blue water flow the flows in remote areas, as well as flood flows and environmental flow requirements, we have left a limited volume of 'available blue water'. Whether blue water consumption for jatropha production at a certain spot is sustainable cannot be measured at the spot or at the river-basin level alone. The question at a global level is: is the blue water footprint of jatropha production sustainable given the larger context, in which freshwater resources are limited and where environmental flow requirements are violated in many places? Consumption of blue water for bio-energy comes on top of blue water consumption for food and other purposes. The specific water consumption for our jatropha case may not lead to any direct violation of environmental flow requirements, but it has forced other sorts of water-consuming crops to other places, because at the place where jatropha is being irrigated also another crop could have been irrigated, a crop that is currently being produced in an area where environmental flow requirements are violated. One may argue that locally sustainable is sustainable, but this reasoning ignores the fact that in the end sustainability is a global issue (Brown et al., 1987).

Table 4.1. Critical questions to be posed when assessing the sustainability of a water footprint.

	Environmental perspective	Social perspective	Economic perspective
Micro-level: local	• Does the green water footprint favour production at the cost of valuable natural vegetation and biodiversity? • Does the blue water footprint violate local environmental flow requirements at any time? • Does the grey water footprint violate local ambient water quality standards?	• Does the water footprint deprive other local water users?	• Is the water productivity optimal? • Can water be saved without reducing the production? • Is the price of water for the user below its real economic cost, resulting in inefficient use? • Is water scarcity factored in into the decision to consume water?
Meso-level: river basin	• Does the blue or green water footprint lead to a changed runoff pattern and thus affect downstream environmental flow requirements? • Does the grey water footprint contribute to violation of ambient water quality standards downstream?	• Does the green, blue or grey water footprint affect downstream users without proper compensation or benefit sharing?	• Is the water allocation in time and space over different users optimal? • Are there opportunity costs by not consuming water for another purpose providing more value? • Are there uncompensated external effects on downstream users?
Macro-level: beyond the river basin, global	• Can the water footprint for the given purpose be sustained given the larger context of limited freshwater availability worldwide and other (possibly more important) competing freshwater demands?	• Is it equitable to have this water footprint for the given purpose given the larger context of limited freshwater availability worldwide and other (possibly more important) competing demands?	• Are regional production patterns of and trade in water-intensive products optimal (efficient) given the larger context of limited freshwater availability and uneven distribution worldwide? • Are low-value water-intensive products exported from a water-scarce region?

4.2. Environmental perspective

As highlighted in the previous section, environmental sustainability can be considered at three distinct levels. Local impacts may occur due to overexploitation or pollution of surface or groundwater bodies or due to a re-allocation of the green evaporative flow from natural vegetation to productive vegetation at the cost of biodiversity. Environmental impacts at the river basin level may occur when many small abstractions or waste flows add up and cause downstream impacts on aquatic ecosystems or terrestrial ecosystems adjacent to the river. At the global level, all water footprints added create the current situation, in which freshwater scarcity leads to overexploitation in many places. A relevant question for the water footprint of any process, product, consumer or producer, is whether the contribution to the total can be reduced or avoided all together. The key question is whether there is a difference between the actual share and the reasonable (sustainable) share of the water footprint in the total water footprint of humanity.

The remainder of this section will focus on how to assess environmental sustainability at the 'catchment level'. What follows can be applied for catchments of various sizes, including river basins as a whole. When catchments are taken small enough (~100 km^2), we are in fact talking about what we call assessment at the 'micro-level'. In this case one includes impacts within the catchment where the footprint occurs, but impacts downstream of the catchment are out of the scope. In practice, however, it is likely that one will consider impacts for larger catchments or river basins as a whole, due to data limitations. We will show how one can identify the hotspots of a water footprint of a product, consumer or producer by looking which water footprint components are located in catchments where water consumption or pollution is at the cost of the quality of natural ecosystems. When one product, consumer or producer has some water footprint in a specific catchment, the impact of that water footprint will always depend on the aggregated water footprint of all activities in that catchment relative to the actually available water resources and assimilation capacity. Therefore, three relevant concepts are introduced: green water scarcity, blue water scarcity and water pollution level. The section will conclude with a discussion of three water footprint impact indices.

In order to identity the hotspots of a water footprint, one needs to know for each type of water footprint (green, blue, grey) in which catchments it is localised and in which periods of the year. A green water footprint in a specific catchment forms a hotspot when in the catchment re-allocation of the green evaporative flow from natural to productive vegetation takes place at the cost of biodiversity beyond a certain acceptable level. The evaporative flow can be appropriated for either human purposes (growing crops or wood) or for sustaining natural vegetation and biodiversity (Figure 4.1). A blue water footprint in a specific catchment forms a hotspot when the environmental flow requirements in the catchment are violated. Finally, a grey water footprint in a specific catchment forms a hotspot when ambient water quality standards in the catchment are violated.

The process of identifying 'water footprint hotspots' in space and time is based on two criteria: (1) the water footprint of a product, consumer or producer is significant in this area and period of the year, and (2) problems of water scarcity or pollution occur in this area in this period of the year. The hotspots will be associated with particular components in the total water footprint of the product, consumer or producer. Hotspots deserve most attention when formulating response measures. The two criteria as formulated above should be made measurable. The precise definition may depend on the purpose of the analysis. One will particularly need to make explicit when a water footprint is considered to be significant in size. Significance can be defined from the perspective of the product, consumer or producer: the water footprint in a certain catchment contributes for example more than 1% to the total water footprint of the product, consumer or producer. Significance can also be defined from the perspective of the area where the water footprint occurs: the water footprint of the product, consumer or producer contributes more than 1% of the total water footprint in that area. One will also need to make explicit what is the minimum level of water scarcity or pollution in an area in order to be classified as hotspot.
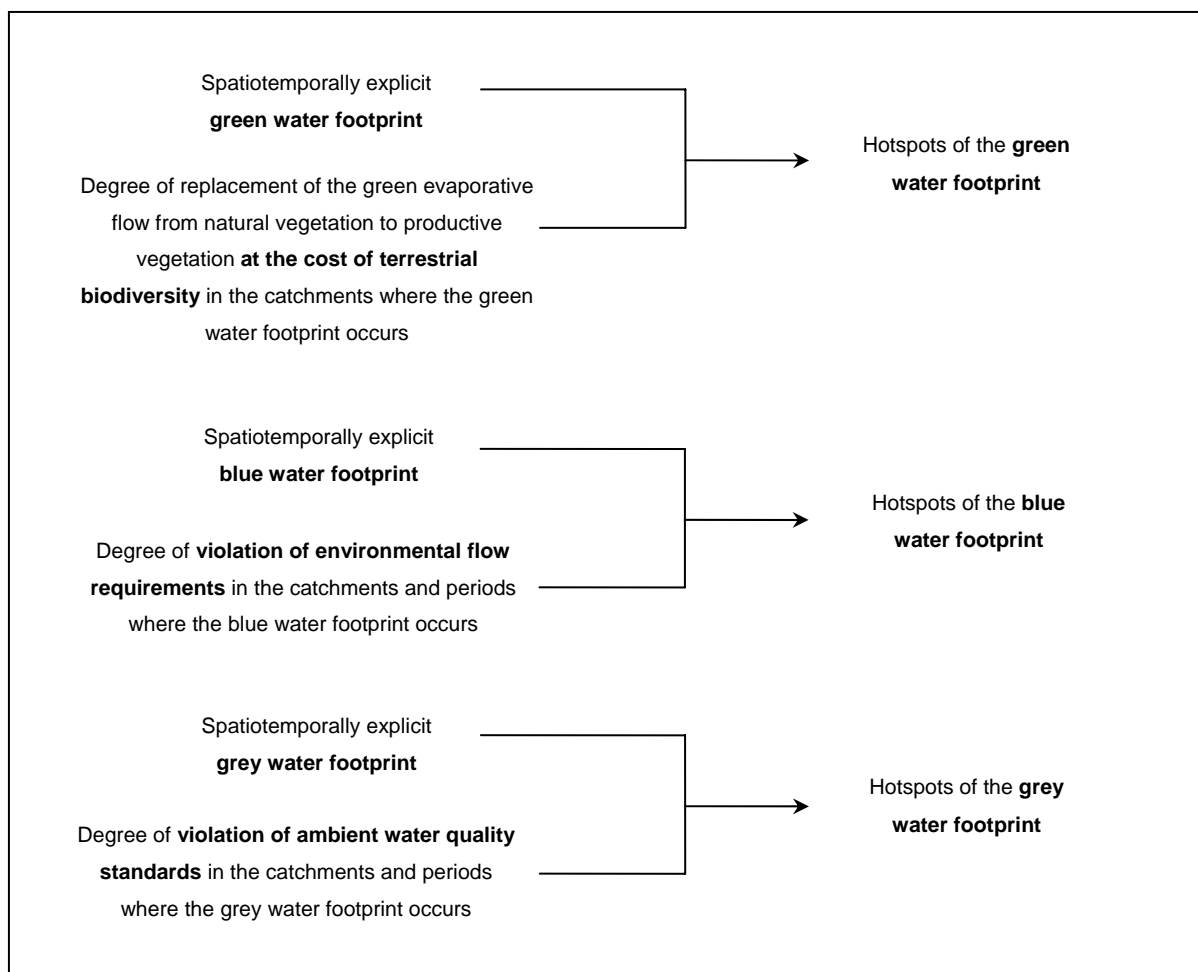
Figure 4.1. Identification of the hotspots of the water footprint of a product, consumer or producer by looking which water footprint components are located in catchments where and periods when water consumption or pollution are at the cost of the quality of natural ecosystems.

Whether a total green water footprint in a catchment is actually significant or not will become clear when it is put in the context of how much green water is available. The green water scarcity in a catchment can be calculated as the ratio of the green water footprint in the catchment and the green water availability (Box 4.1). The latter is equal to the total evapotranspiration of rainwater from land minus evapotranspiration from land reserved for natural vegetation and minus evapotranspiration from land that cannot be made productive. Next to green water scarcity it can be relevant to look at the extent to which the total green water footprint in a catchment results in a changed runoff pattern downstream. Often, evapotranspiration of rainfall from a crop field will not differ much from evapotranspiration from the field under natural conditions, but it may differ significantly during particular parts of the year (SABMiller and WWF-UK, 2009). At times evapotranspiration may be lower, at other times higher, leading to increased or reduced runoff respectively. This, in turn, can affect downstream environmental flow requirements. It has been suggested to speak about the 'net green water footprint' to refer to the difference between the evapotranspiration from the crop and the evapotranspiration under natural conditions. This terminology, however, is not consistent with the basic definition of the water footprint concept as an indicator of freshwater appropriation, which requires that we look at totals. We

recommend to speak about 'changed runoff as a result of the green water footprint' instead of 'net green water footprint'. The issue of changed runoff as a result of green water use in agriculture can best be addressed in the sustainability assessment phase, not in the water footprint accounting phase.

Box 4.1. *Green water scarcity: the green water footprint in a catchment compared to green water availability.*

When people speak about water-scarcity indicators, they generally refer to indicators of blue water scarcity. However, also green water availability is limited, so green water resources are also scarce. The level of green water scarcity depends on the green water use versus the green water availability. To be more precise: the green water scarcity in a catchment x is defined as the ratio of the total green water footprint in the catchment to the green water availability.

$$WS_{green}[x,t] = \frac{WF_{green}[x,t]}{WA_{green}[x,t]}$$

Measuring can be done at daily basis, but a monthly basis will generally be sufficient to see the variation within the year. The green water availability (WA_{green}) in a catchment x is defined as the total evapotranspiration of rainwater (ET_{green}) minus evapotranspiration from land reserved for natural vegetation (ET_{env}) and minus the evapotranspiration that cannot be made productive:

$$WA_{green}[x,t] = ET_{green}[x,t] - ET_{env}[x,t] - ET_{unprod}[x,t]$$

All variables are expressed here in terms of volume/time. ET_{env} refers to the quantity of green water needed to sustain terrestrial ecosystems and biodiversity and human livelihoods that depend on these ecosystems. ET_{unprod} refers to evapotranspiration that cannot be made productive in crop production, i.e. evapotranspiration in areas or periods of the year that are unsuitable for crop growth. The average green water scarcity over the year can be obtained by taking the average of the monthly values of the green water scarcity:

$$WS_{green,avg}[x] = \frac{\sum\limits_{t=1}^{12} WS_{green}[x,t]}{12}$$

It would be even more accurate to take the average of daily values of the green water scarcity, but this is much more data demanding; the monthly approach will generally give a good approximation.

The total blue water footprint in a catchment is equal to the aggregate of all blue process water footprints within the catchment. The effect of this total blue water footprint depends on the available blue water in the catchment, which is equal to the runoff from the catchment minus the so-called 'environmental flow requirements'. The latter can be formulated in terms of the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. Environmental flow requirements form boundaries for runoff alteration, comparable to the way in which water quality standards form boundaries for pollution (Richter, 2009). Appendix III discusses the concept of environmental flow requirement in more detail. Figure 4.2 shows how the blue water footprint over the year can be compared with the blue water availability over the year. In the case shown, environmental flow requirements are violated during a certain period of the year, but not during the rest of the year. The blue water scarcity in a catchment can be calculated by taking the ratio of the blue water footprint to the blue water availability (Box 4.2). Because both the blue water footprint and the blue water availability vary within the year, water scarcity will fluctuate within the year as well. Blue water scarcity can therefore best be calculated with a resolution of a month or with an even finer resolution if intra-annual variability is very large.
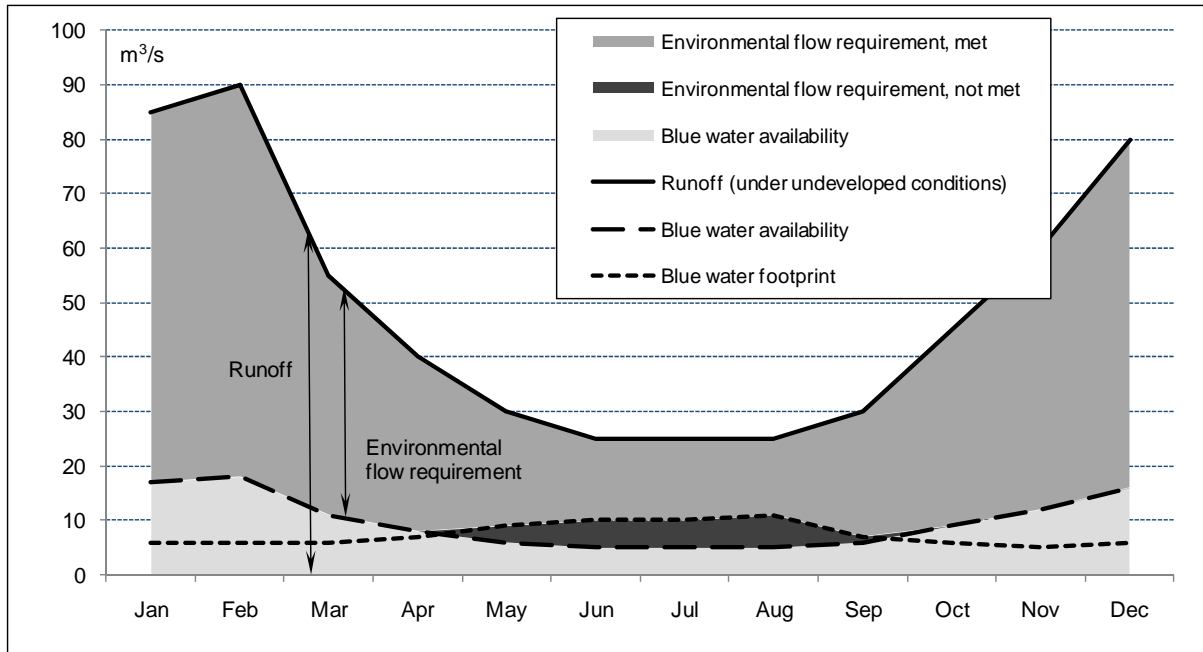
Figure 4.2. *The blue water footprint over the year compared to blue water availability, where the latter is equal to runoff (under undeveloped conditions) minus environmental flow requirements.*

The effect of the total grey water footprint in a catchment depends on the runoff in the catchment available to assimilate the waste. The water pollution level in a catchment can be calculated by taking the ratio of the grey water footprint to the runoff (Box 4.3). Both the grey water footprint and the runoff vary within the year, so that the water pollution level will fluctuate within the year as well. In most cases calculation per month is probably good enough to represent the variation in time.

When a certain product, consumer or producer contributes to the total blue water footprint in a catchment, the impact of that depends on two factors: (1) how large is the contribution, and (2) what is the blue water scarcity in the catchment. For the green water footprint the same rationale can be followed. Similarly, when a certain product, consumer or producer contributes to the total grey water footprint in a catchment, the impact of that depends on: (1) how large is the contribution, and (2) what is the water pollution level in the catchment. Green and blue water footprint impact indices can be calculated by multiplying the size of the water footprint by the blue or green water scarcity. A grey water footprint impact index can be calculated by multiplying the size of the grey water footprint by the water pollution level (Box 4.4). Water footprint impact indices are useful only as crude indicators of the environmental impact at catchment level; the aggregated indices do no longer contain spatial or temporal information. As a basis for formulating appropriate response measures, it is more useful to identify 'hotspots' as explained earlier than to calculate aggregated water footprint impact indices. It should also be noted that the impact indices discussed here aim to measure environmental impacts at the catchment level; for assessing sustainable water allocation, indices that reflect local impacts are not helpful. For this purpose one can better use the volumetric water footprint accounts, because allocation is about apportioning scarce resources, not about local impacts.

Water-scarcity indicators are always based on two basic ingredients: a measure of water use and a measure of water availability. The most common indicator of water scarcity is the ratio of the annual water withdrawal in a certain area to the total annual runoff in that area, called variously the water utilization level (Falkenmark, 1989), the withdrawal-to-availability ratio (Alcamo and Henrichs, 2002) or the use-to-resource ratio (Raskin et al., 1996). There are three critiques to this approach. First, water withdrawal is not the best indicator of water use when one is interested in the effect of the withdrawal at the scale of the catchment as a whole, because water withdrawals partly return to the catchment. Therefore it makes more sense to express blue water use in terms of consumptive water use, i.e. by considering the blue water footprint. Second, total runoff is not the best indicator of water availability, because it ignores the fact that part of the runoff needs to be maintained for the environment. Therefore it is better to subtract the environmental flow requirement from total runoff (Smakhtin et al., 2004a,b). Finally, it is not so accurate to consider water scarcity by comparing *annual* values of water use and availability. In reality, water scarcity manifests itself rather at monthly than annual scale, due to the intra-annual variations of both water use and availability. In the context of water footprint studies, the 'blue water scarcity' in a catchment is defined such that the three weaknesses are repaired. The 'blue water scarcity' in a catchment x (WS_{blue}) is defined as the ratio of the total blue water footprint in the catchment (WF_{blue}) to the blue water availability (WA_{blue}). A blue water scarcity of hundred percent means that the available blue water has been fully consumed.

$$WS_{blue}[x,t] = \frac{WF_{blue}[x,t]}{WA_{blue}[x,t]}$$

The blue water scarcity is time-dependent; it varies within the year and from year to year. Measuring can be done at daily basis, but a monthly basis will generally be sufficient to see the variation within the year. The blue water availability (WA_{blue}) in a catchment x is defined as the runoff (R) minus environmental flow requirements (EFR):

$$WA_{blue}[x,t] = R[x,t] - EFR[x,t]$$

The average blue water scarcity over the year can be obtained by taking the average of the monthly values of the blue water scarcity:

$$WS_{blue,avg}[x] = \frac{\sum_{t=1}^{12} WS_{blue}[x,t]}{12}$$

It would be even more accurate to take the average of daily values of the blue water scarcity, but this is much more data demanding; the monthly approach will generally give a good approximation. Note that the average blue water scarcity in a year that is calculated in this way will often significantly differ from the case in which one would take the ratio of the annual blue water footprint over annual blue water availability.

The 'water pollution level' is an indicator of the degree of pollution of a water flow. It is measured as the fraction of the pollution assimilation capacity consumed, i.e. by taking the ratio of the total grey water footprint in a catchment (WF_{grey}) to the runoff from that catchment (R). A water pollution level of hundred percent means that the pollution assimilation capacity has been fully consumed.

$$WPL[x,t] = \frac{WF_{grey}[x,t]}{R[x,t]}$$

The average water pollution level over the year can be obtained by taking the average of the monthly values of the water pollution level:

$$WPL_{avg}[x] = \frac{\sum_{t=1}^{12} WPL[x,t]}{12}$$

The monthly approach will generally give a good approximation; if necessary, it is possible of course to take a smaller time step.

Box 4.4. *Water footprint impact indices at catchment level.*

The water footprint is a volumetric measure, showing freshwater consumption and pollution in time and space. At the catchment level, water footprints are relevant by providing information on how water resources are allocated to different purposes. The volumes as such are key information in the allocation discussion, but do not provide information on whether they contribute to immediate problems of water scarcity or pollution within the catchment. For that purpose one will need to put the blue water footprint of a specific product, consumer or producer in the context of the blue water scarcity in the catchment where the footprint occurs. Similarly, the green water footprint needs to be considered in the context of green water scarcity. The grey water footprint of a specific product, consumer or producer in a catchment needs to be regarded in the context of the water pollution level in the catchment.

The 'green water footprint impact index' ($WFII_{green}$) is an aggregated and weighed measure of the environmental impact of a green water footprint. It is based on two inputs: (1) the green water footprint of a product, consumer or producer specified by catchment x and by month t, (2) the green water scarcity by catchment and by month. The index is obtained by multiplying the two matrices and then summing the elements of the resultant matrix. The outcome can be interpreted as a green water footprint weighed according to the green water scarcity in the places and periods where the various green water footprint components occur.

$$WFII_{green} = \sum_x \sum_t \left(WF_{green}[x,t] \times WS_{green}[x,t] \right)$$

The 'blue water footprint impact index' ($WFII_{blue}$) is an aggregated and weighed measure of the environmental impact of a blue water footprint. It is based on: (1) the blue water footprint of a product, consumer or producer specified by catchment x and by month t, (2) the blue water scarcity by catchment and by month. The index is obtained by multiplying the two matrices and then summing the elements of the resultant matrix. The outcome can be interpreted as a blue water footprint weighed according to the blue water scarcity in the places and periods where the various blue water footprint components occur.

$$WFII_{blue} = \sum_x \sum_t \left(WF_{blue}[x,t] \times WS_{blue}[x,t] \right)$$

The 'grey water footprint impact index' ($WFII_{grey}$) is an aggregated and weighed measure of the environmental impact of a grey water footprint. It is based on: (1) the grey water footprint of a product, consumer or producer specified by catchment x and by month t, (2) the water pollution level by catchment and by month. The index is obtained by multiplying the two matrices and then summing the elements of the resultant matrix. The outcome can be interpreted as a grey water footprint weighed according to the water pollution level in the places and periods where the various grey water footprint components occur.

$$WFII_{grey} = \sum_x \sum_t \left(WF_{grey}[x,t] \times WPL[x,t] \right)$$

The three water footprint impact indices refer to different sorts of water use which are not comparable. In order to have an overall water footprint impact index one could simply add the three indices. Since green water scarcity is generally lower than blue water scarcity, the green water footprints will count less than the blue water footprints.

As a general note, we would like to emphasise that the impact indices as discussed here have a very limited value. The reason is that the useful information for response is contained in the underlying variables. It is relevant to know the size and colour of a water footprint, to know when and where it occurs and in which context (degree of water scarcity, water pollution level). Aggregating this information into three indices or synthesizing the three into one overall index means that all information is covered. What remains is a crude impression of the local environmental impact of a water footprint as a whole, which can be useful when one aims to roughly compare it with the local impact of another water footprint, but is not useful as a basis for formulating specific response measures. It should also be noted that the above water footprint impact indices account for environmental impacts only, not social or economic impacts. Besides, they show impacts at catchment level; for considerations of sustainable water use, the volumetric accounts provided by the water footprint indicator are more useful. The main reason to provide the indices here is because of the existing demand for such indices within the LCA community.

4.3. Social perspective

From a social perspective, the sustainability of a water footprint will be related to issues like equitable sharing, external effects, free-ridership, employment, and human health. The issue of equitable sharing comes in for example when locally there is a large water consumer (e.g. with a large blue and/or grey water footprint) making profit with producing export products while communities around do not have access to clean drinking water supply. At a river basin scale the issue of equitable sharing comes to the front when large-scale upstream water consumptive abstraction and pollution take place at the cost of downstream water users. At a global scale equitability is relevant given the fact that some consumers have a five times larger water footprint than others while global freshwater resources are limited. The question is: who gets which part of the pie? Are freshwater resources in Mexico used for producing maize for biofuel in the USA or for producing maize for domestic food consumption? When the first happens, it automatically will raise the question on fairness. Apart from the issue of equitability within our own generation, there is the issue of intergenerational equity. The question here is how fair it is towards future generations if groundwater or lake-water levels go down or pollution levels go up as a result of today's activities.

External effects are very frequent in water resources use: the costs of consumption and pollution on downstream people are generally not compensated for by the upstream water user. Free-ridership is a typical phenomenon as well, where some individuals abstract more water from the aquifer or river than others at the expense of all.

Another issue is employment. It happens in many places that crop production in a catchment leads to overexploitation of the available water resources, which is shown for example by declining groundwater tables. This sort of water footprint obviously needs to be reduced. This, however, can be at the cost of regional employment and therefore undesired. Water footprints are often particularly high because of water use in agriculture, which in many countries is a major sector of employment.

Finally, the grey water footprint may affect human health, both at the point of waste disposal as downstream.

4.4. Economic perspective

A certain water footprint can always be associated with the creation of a certain economic value. Fresh water can be regarded as a factor of production. Ideally, fresh water will be used such that it creates the highest welfare (where welfare is interpreted in its broadest sense, including any societal value considered relevant). In practice, however, few of the conditions required for efficient water use are met. Water supply is often heavily subsidised, water is often not allocated to the purposes where it creates the highest societal benefit and water scarcity, pollution and external costs of water supply are generally not translated into a cost for the water user. As a consequence, the resulting patterns of water use are generally far from the economic optimum. The welfare lost in this way is what we can regard as the (negative) economic impact of water footprints as they are.

There are various reasons why the conditions for efficient water use are not met. There are two most important ones. First, due to the public character of water and the natural absence of private ownership, there is no market that establishes a price of freshwater that is based on supply and demand and reflects scarcity. Second, partly as a result of the former, users generally pay a price for freshwater that is far below its real economic value. Most governments subsidise water supply on a huge scale by investing in infrastructure like dams, canals, water purification, distribution systems and wastewater treatment. These costs are often not charged to the water users. As a result, there is insufficient economic incentive for water users to save water. Besides, water scarcity is generally not translated into an additional component in the price of goods and services that are produced with the water, as happens naturally in the case of private goods. Finally, water users generally do not pay for the negative impacts that they cause on downstream people or ecosystems. As a result, water inputs do not form a substantial component of the total price of even the most water-intensive products. Consequently, the production of goods – even though various sorts of goods require a lot of scarce water inputs – is not or hardly governed by water scarcity.

The economic impact of a water footprint is thus related to water use inefficiency. One can distinguish three levels at which one can consider water use efficiency: the local, river basin and global level (Hoekstra and Hung, 2002, 2005). At a local level, that of the water user, the question is whether one could use less water producing the same good or service and achieving the same benefit. The focus here is at the amount of goods produced per unit of water. In agriculture, the question becomes: can we get more 'crop per drop'. Local water use efficiency, sometimes called 'productive efficiency', can be expressed in terms of product units per unit of water (e.g. ton/m^3). It can be increased by stimulating water-saving technology, e.g. by charging prices based on full marginal cost, subsidising better technology, taxing water-wasting technology and/or creating awareness among the water users about the value of water saving.

At the catchment or river basin level, the question is how the scarcely available water resources are allocated among competing uses. The question is now: can we get more 'value per drop'. Water use efficiency at this level, also called 'allocation efficiency' is expressed in terms of monetary value obtained per unit of water (e.g. euro/m^3). It can be enhanced by re-allocating water to those places and purposes that generate the highest marginal benefits.

Finally, at the level beyond that of a river basin, the question is which regions in the world have a comparative advantage in producing water-intensive goods and which regions a comparative disadvantage. Where one country may have a comparative advantage in one product type (e.g. wheat), another country may have a comparative advantage in another product type (e.g. olives, grapes). 'Global water use efficiency' can be increased if nations use their comparative advantages and disadvantages to either encourage or discourage certain types of production. Factors that influence whether a country has a comparative advantage or disadvantage in producing a certain water-intensive product are for example: regional climate, the degree of regional water scarcity and availability and actual use of water technology. And of course other factors than

water – e.g. land and labour productivity – will influence the extent to which countries have a comparative advantage or disadvantage in certain types of production.

Calculating 'the economic impact' of a water footprint is a difficult task. It is difficult, because economic analysis requires a broad analysis, including all production factors, not just water. Water footprint accounts alone provide only a small subset of the information necessary for a full economic analysis. An economic analysis that focuses on water as an input factor will be no more than a partial analysis, which means that no general economic conclusions can be drawn from it. A partial analysis, focussing on the economics of water use, is possible and useful, however, as one of the inputs into a broader analysis. In order to review the economic impact of a water footprint, one can best consider the three levels discussed above: the local, basin and beyond-basin level.

At the local level, one can make a first crude estimate of the economic impact by considering the economic loss by not using the best technology available:

Economic loss per water unit = product price × (potential water productivity – actual water productivity)

Water productivities are expressed for instance in ton/m^3 and product price in euro/ton. Note that 'water productivity' is the inverse of the 'water footprint'. This equation is obviously oversimplified because it assumes that (a) potential water productivity can be achieved at the same cost as actual water productivity, (b) the water units saved by the higher productivity can be used to produce more of the same product, and (c) the product price remains equal. Alternatively, one can calculate the economic loss per product unit instead of per water unit:

Economic loss per product unit = economic value of water × (actual water footprint − potential water footprint)

This equation is based on the only assumption that potential water productivity (potential water footprint) can be achieved at the same cost as actual water productivity (actual water footprint). If the assumption is not true, one can correct for that by subtracting from the obtained loss per product unit the cost made to achieve the higher productivity (lower water footprint). A drawback of above equation is that it requires data on the economic value of water, which are generally hard to obtain.

At the catchment or river basin level, one can make a first crude estimate of the economic impact of a water footprint by taking the difference between the potential and actual economic water productivity:

Economic loss per water unit = potential economic water productivity – actual economic water productivity

Economic water productivities are expressed in euro/m^3. Economic water productivity is equal to water productivity in physical terms (product units per unit of water) times the product price (monetary value per

product unit). The potential economic water productivity is higher than the actual one when water in a river basin can be allocated to other places and purposes where the water has a higher added value. The above equation is only true for marginal changes in water allocation. One will generally see that high-value crops (e.g. vegetables, grapes, citrus fruits, olives) have a higher economic water productivity than low-value crops (like cereals, see Figure 4.3). It seems therefore attractive in water-scarce areas suitable for high-value crops to replace all cereals by high-value crops. Shifting gives economic benefit indeed, but when it happens on a large scale, other factors come into play as well, since the demand for high-value crops is limited, so prices will drop. Besides, there is also a value in some degree of local or regional food self-sufficiency (which requires cereals as well), so that replacing all cereals may not be desirable. It is very common in water studies to carry out the above type of economic analysis and make conclusions about the value of water re-allocation based on a comparison of economics water productivities alone. One should, however, be very careful in doing so, because conclusions about re-allocation should be based on a full and not partial economic analysis and take into account non-economic considerations as well.
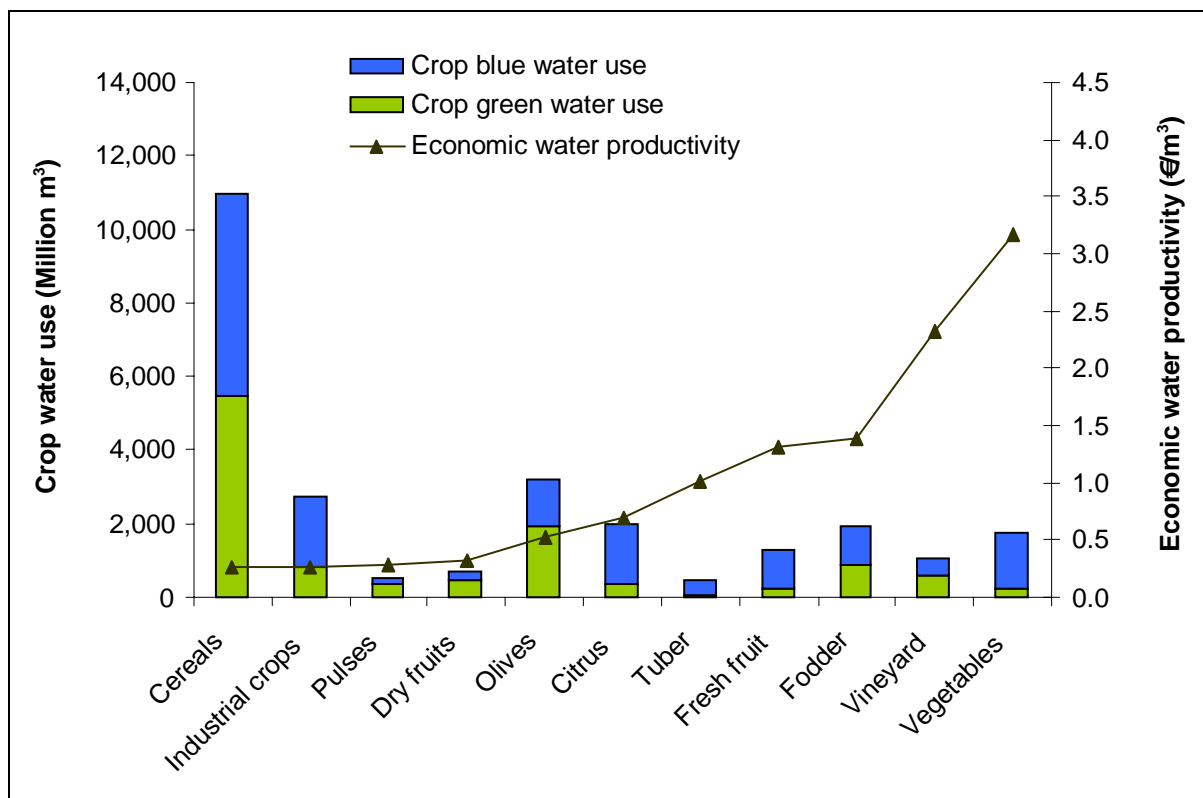
Figure 4.3. *Economic water productivity (€/m³) and blue and green crop water use in Spanish agriculture for the year 2006. Source: Garrido et al. (2009).*

At the level beyond the river basin, economic impacts of certain production patterns can be analysed by considering the comparative advantages and disadvantages that different regions may have (Wichelns, 2004). Table 4.2 gives a hypothetical example of two countries A and B and two crops X and Y. Although country B has an *absolute disadvantage* for both crops – because for both crops the water productivity is lower than in country A – it does have a *comparative advantage* in crop Y. Country A has a comparative advantage in crop X.

This means that both countries can save water by specialising in the production of the crop where they have a comparative advantage. They can fulfil the demand for the other crop by trade. Not allocating the water to the crop where a country has a comparative advantage thus results in an opportunity cost, the economic cost of the existing allocation pattern. It should be noted that the example given here is simplified for the purpose of illustration. It is assumed that water is the critical scarce resource in both countries. In reality other inputs count as well, so one should take the relative productivities and scarcities of those other input factors into account as well when assessing where countries do have a comparative advantage. Besides, productivities can change, resulting in a changing starting point for the analysis. Finally, other considerations are relevant as well, like for example the aim of some degree of self-sufficiency in each crop.

Table 4.2. A hypothetical example illustrating the potential water saving in two trading countries when country A uses its comparative advantage in crop X and country B its comparative advantage in crop Y.

		Country A	Country B	Total
Water footprint	Crop X	1000 m^3/ton	2000 m^3/ton	
	Crop Y	500 m^3/ton	800 m^3/ton	
Water productivity	Crop X	1000 ton/Mm^3	500 ton/Mm^3	
	Crop Y	2000 ton/Mm^3	1250 ton/Mm^3	
Demand	Crop X	1×10^6 ton	1×10^6 ton	2×10^6 ton
	Crop Y	1×10^6 ton	1×10^6 ton	2×10^6 ton
Production scenario without crop trade	Crop X	1×10^6 ton using 1000×10^6 m^3	1×10^6 ton using 2000×10^6 m^3	2×10^6 ton
	Crop Y	1×10^6 ton using 500×10^6 m^3	1×10^6 ton using 800×10^6 m^3	2×10^6 ton
		Total water use: 1500×10^6 m^3	Total water use: 2800×10^6 m^3	
Production scenario with crop trade	Crop X	1.44×10^6 ton using 1440×10^6 m^3	0.56×10^6 ton using 1120×10^6 m^3	2×10^6 ton
	Crop Y	zero	2×10^6 ton using 1600×10^6 m^3	2×10^6 ton
		Total water use: 1440×10^6 m^3	Total water use: 2720×10^6 m^3	
Water saving through trade		60×10^6 m^3	80×10^6 m^3	140×10^6 m^3

5. Library of water footprint response options

5.1. Shared responsibility

One can argue that consumers are responsible for what they consume, so also for the indirect resource use they have through their consumption pattern. In this sense, consumers have responsibility for their water footprint and should undertake action to ensure that their water footprint is sustainable. If they would do so, producers would be forced to deliver sustainable products. One can also turn the argument around and argue that producers are responsible for delivering sustainable products. This would imply that producers should take action to make product water footprints sustainable. And investors, of course, should include considerations of sustainable water use into their investment decisions. Finally, water is a public good, so governments cannot withdraw from their responsibility to put proper regulations and incentives in place to ensure sustainable production and consumption. It will be maintained here that consumers, producers, investors and governments all have a shared responsibility. This chapter will review options available to consumers, producers, investors and governments to reduce water footprints and particularly mitigate impacts.

It is absolutely not the purpose here to be prescriptive in the sense that this manual says what to do. The manual is restricted to an inventory of options. Since this is a first version of such an inventory, it does by no means claim to be exhaustive. Nevertheless, it may be a helpful guide in understanding along which lines alternative response strategies can be formulated. A response strategy can be a combination of one or more of the options identified here.

5.2. Reducing the water footprint of humanity: what is possible?

Technically, both blue and grey water footprints in industries and households can be reduced to zero, by full water recycling. In a closed cycle there will be neither evaporation losses, nor polluted effluents. There are a few exceptions, where the blue water footprint of a process cannot completely be reduced to zero, think about cases where water is applied in the open air by necessity, so that some evaporation cannot be avoided. But in factories or cooling systems, evaporated water can be captured and recycled or returned to the water body where it was taken from.

In agriculture, the grey water footprint can be reduced to zero by preventing the application of chemicals to the field. It can be lowered substantially by applying less chemicals and employing better techniques and timing of application (so that less chemicals arrive in the water system by runoff from the field or by leaching). Green and blue water footprints (m^3/ton) in agriculture can generally be reduced substantially by increasing water productivity (ton/m^3). Agriculture is often focussed on maximising land productivity (ton/ha), which makes sense when land is scarce and freshwater is abundant, but when water is scarcer than land, maximising water productivity is more important. This implies applying less irrigation water in a smarter way, in order to give a higher yield per cubic metre of water evaporated.

The general guideline for water footprint reduction is: avoid, reduce and compensate (in this order, see Figure 5.1). In all cases, priority is to be given to those water footprint components that are located in hotspots, i.e. areas where problems of water scarcity and pollution are most severe and where the water footprint of the consumer or producer is significant.
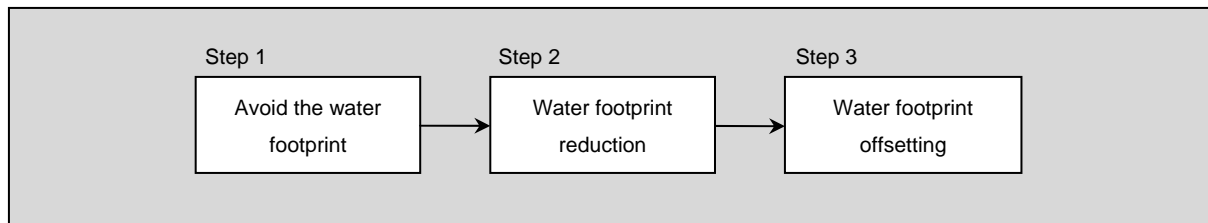
Figure 5.1. *The three subsequent steps in water footprint reduction and offsetting.*

It is often thought that water footprint reduction is only relevant in locations where problems of water scarcity and pollution exist. One can pose the rhetoric question why to reduce the water footprint in an area where water is abundantly available? Or why to reduce the green water footprint in agriculture if the rain comes anyhow and will otherwise remain unproductive? The rationale behind these questions is: when locally the water does not get depleted, the water use must be sustainable. This sort of thinking is based on the misconception that sustainable water use can be measured locally. A very rough sketch of the global situation, however, is the following: (1) one can encounter relatively low water productivities (e.g. large water footprints per ton of crop) in many water-abundant areas, and (2) one can often find relatively high water productivities (small water footprints per ton) in areas where water is scarce. Problems of water depletion are concentrated in the water-scarce areas. The misconception is that there is no water issue in water-abundant areas and that the attention should go to the water-scarce areas. Counter-intuitively, the solution greatly lies in the water-abundant areas. Low water productivities (large water footprints) in water-abundant areas are a waste. Increasing the water productivity (i.e. reducing the green and blue water footprints) in agriculture in water-abundant areas increases global production from water-rich areas, thus reducing the need for water-intensive products from water-scarce areas, and therefore helping to release the pressure on the blue water resources in water-scarce areas. So, from a global sustainability perspective, water footprints per ton of product need to be reduced everywhere when possible, also in water-abundant areas.

The concept of water footprint offsetting is still ill-defined. In general terms it means: taking measures to compensate for the negative impacts of the water footprint that remains after reduction measures have been implemented. But the two weak points in the definition are that (1) it does not specify which sort of compensation measures and which level of compensation are good enough to offset a certain water footprint impact and (2) it does not specify which impacts should be compensated precisely and how to measure those impacts. In the previous chapter we have seen that the term 'impact' can be interpreted very broadly. The fact that the offset concept is ill-defined means that it can easily be misused. Without a clear definition, measures taken under the banner of 'offset' can potentially be a form of greenwashing rather than a real effort aimed at full compensation. For this reason, we strongly recommend to focus response on the step of avoiding and

reduction of water footprints and to look at offsetting as a real last step only. Another reason is that water footprints and their associated impacts are always local. In this respect, the water footprint is markedly different from the carbon footprint. The idea of a global offset market as has developed over the past few years for carbon footprint offsets does not make sense for water. An offset of a water footprint should always occur in the catchment where the water footprint is located. This drives the attention to the own water footprint again and does not allow to think in terms of general compensation schemes where one can simply 'buy' an offset.

Closely related to the concept of water footprint offset is the idea of water neutrality (Box 5.1). Water neutrality is the umbrella term for avoiding, reduction and offsetting. It carries similar problems as the concept of water footprint offsetting. We will not use it in the remainder of the chapter and recommend others to give priority to set quantitative targets with respect to the reduction of water footprints and associated impacts rather than using terms like offsetting and neutrality. And when the terms are used nevertheless, one should take extreme care to clarify what is meant precisely.

Box 5.1. *Water neutrality.*

'Water neutral' means that one reduces the water footprint of an activity as much as reasonably possible and offsets the negative externalities of the remaining water footprint (Hoekstra, 2008a). In some particular cases, when interference with the water cycle can be completely avoided – e.g. by full water recycling and zero waste – 'water neutral' means that the water footprint is nullified; in many other cases, like in the case of crop growth, water consumption cannot be nullified. Therefore 'water neutral' does not always mean that water consumption is brought down to zero, but that the negative economic, social and environmental externalities are reduced as much as possible and that the remaining impacts are fully compensated. Compensation can be done by contributing to (investing in) a more sustainable and equitable use of water in the hydrological units in which the impacts of the remaining water footprint are located.

Water neutral is a strong concept in the sense that it attracts broad interest, invites for positive action and sounds good. Some companies like the concept for that reason. The water-neutral concept offers a great opportunity to translate water footprint impacts into action to mitigate those impacts within both communities and businesses. However, there are a number of important questions that need to be answered clearly as a precondition for the success of the water-neutral concept. These are for example: How much reduction of a water footprint can reasonably be expected? What is an appropriate water-offset price? What type of efforts count as an offset? As long as these sorts of questions have not been answered yet – the risk of the water neutrality concept is that its content depends on the user. As a result, some may use it to refer to real good measures taken in both operations and supply chain while others may use it in a way that can rather be interpreted as a way of 'greenwashing'. The risk with the water-neutral concept is also that the focus will shift from water footprint reduction to offsetting. A water footprint can be measured empirically, so can its reduction. Defining offsetting and measuring its effectiveness is much more difficult, enlarging the risk of misuse. Besides, compensating measures should be considered a last resort option, to be looked at after having reduced the own water footprint first.

5.3. Consumers

The water footprint of a consumer is sustainable when (a) the total remains below the consumer's fair share of the available green and blue freshwater resources in the world, and (b) no component of the total water footprint presses at places where or times when local environmental flow requirements or ambient water quality standards are violated.

Consumers can reduce their direct water footprint (home water use) by installing water saving toilets, applying a water-saving showerhead, closing the tap during teeth brushing, using less water in the garden and by not disposing medicines, paints or other pollutants through the sink.

The indirect water footprint of a consumer is generally much larger than the direct one. A consumer has basically two options to reduce his or her indirect water footprint. One option is to change the consumption pattern by substituting a specific consumer product that has a large water footprint by another type of product that has a smaller water footprint. Examples: eat less meat or become vegetarian, drink plain water instead of coffee, or wear less cotton and more artificial fibre clothes. This approach has limitations, because many people don't easily shift from meat to vegetarian and people like their coffee and cotton. A second option is to select the cotton, beef or coffee that has a relatively low water footprint or that has its footprint in an area that doesn't have high water scarcity. This requires, however, that consumers have proper information to make that choice. Since this information is generally not available in the world of today, an important thing consumers can do now is ask product transparency from businesses and regulation from governments. When information is available on the impacts of a certain article on the water system, consumers can make conscious choices about what they buy.

5.4. Companies – corporate water footprint strategy

A corporate water footprint strategy can include a variety of targets and activities (Table 5.1). Businesses can reduce their operational water footprint by reducing water consumption in their own operations and bringing water pollution to zero. Keywords are: avoid, reduce, recycle and treat before disposal. By avoiding any evaporation, the blue water footprint can be reduced to zero. By reducing the production of wastewater as much as possible and by treating the wastewater still produced, the grey water footprint can be reduced to zero as well. Treatment can be done within the own facilities or by a public wastewater treatment facility; it is the quality of the water finally discharged into the ambient water system that determines the grey water footprint.

For most businesses, the supply-chain water footprint is much larger than the operational footprint. It is therefore crucial that businesses address that as well. Achieving improvements in the supply chain may be more difficult – because not under direct control – but they may be more effective. Businesses can reduce their supply-chain water footprint by making supply agreements including certain standards with their suppliers or by simply changing to another supplier. In many cases it probably means quite something, because the whole business model may need to be transformed in order to incorporate or better control supply chains and to make supply chains fully transparent to consumers.

A company can also aim to reduce the consumer water footprint that is inherent to the use of their product. When a consumer uses soap, shampoo, cleaning chemical or paint, it is likely that he will flush it through the drain. When the water is not treated or when the chemical is such that it is not or only partly removed, this will

give a grey water footprint that could have been avoided when the company had used substances that are less toxic, less harmful and more easily degradable.

Table 5.1. Corporate water footprint response options.

Water-footprint reduction targets – operations
• Benchmarking products or sites. Define best practice and formulate targets to achieve best practice throughout the business. Can be done in own company or within a sector as a whole.
• Reduction of blue water footprint in general. Reduction of consumptive water use in operations by recycling, adopt water-saving appliances, replace water-intensive by water-extensive processes.
• Reduction of blue water footprint in hotspots. Focus above measures in water-scarce areas or in areas where environmental flow requirement in a river are violated or where groundwater or lake levels are dropping.
• Reduction of grey water footprint in general. Reduce wastewater volume; recycle chemicals. Wastewater treatment before disposal.
• Reduction of grey water footprint in hotspots. Focus above measures in areas where ambient water quality standards are violated.

Water-footprint reduction targets – supply chain
• Agree on reduction targets with suppliers.
• Shift to other supplier.
• Get more or full control over the supply chain. Change business model in order to incorporate or get better control over the supply chain.

Water-footprint reduction targets – end use
• Reduce inherent water requirements in use phase. Reduce expected water use when product is used (e.g. dual flush toilets, dry sanitation equipment, water-saving showerheads, water-saving washing machines, water-saving irrigation equipment).
• Reduce risk of pollution in use phase. Avoid or minimise the use of substances in products that may be harmful when reaching the water (e.g. in soaps, shampoos).

Water-footprint offsetting measures
• Environmental compensation. Invest in improved catchment management and sustainable water use in the catchment where the company's (residual) water footprint is located.
• Social compensation. Invest in equitable water use in the catchment where the company's (residual) water footprint is located, e.g. by poverty alleviation and improved access to clean water supply and sanitation.
• Economic compensation. Compensate downstream users that are affected by intensive upstream water use in the catchment where the company's (residual) water footprint is located.

Product & business transparency
• Conform to shared definitions and methods. Promote and adopt globally shared definitions and methods of water footprint accounting and sustainability assessment.
• Promote water accounting over the full supply chain. Cooperate with others along the supply chain to be able to produce full accounts for final products.
• Corporate water footprint reporting. Report water-related efforts, targets and progress made in annual sustainability report, also covering the supply-chain.
• Product water footprint disclosure. Disclosure of relevant data through reporting or internet.
• Product water labelling. Same as above, but now putting the information on a label, either separate or included in a broader label.
• Business water certification. Promote and help setting up a water certification scheme and conform to it.

Engaging with consumers and civil society organisations
• Consumer communication

Engaging with governments
• Proactively work with governments on developing relevant regulation and legislation

Among the various alternative or supplementary tools that can help improving transparency are: conform to shared definitions and methods (as for example promoted by the Water Footprint Network), water footprint reporting and disclosure of relevant data. Clarity about activities undertaken to reduce the corporate water footprint can be enhanced by setting quantitative water-footprint reduction targets in time. A potential tool within large companies or in specific sectors is benchmarking: what can be achieved in (the supply chain of) one factory should also be possible in (the supply chain of) another factory.

Farming is a sort of business for which the same things apply as discussed above. For livestock farmers a major concern should be the water footprint of the feed they buy or produce themselves. For crop farmers, a number of specific water footprint reduction options are available as listed in Table 5.2.

Table 5.2. *Options for crop farmers to reduce their water footprint.*

Reduce green water footprint in crop growth
• Increase land productivity (yield, ton/ha) by improving agricultural practice; since the rain on the field remains the same, water productivity (ton/m^3) will increase and the green water footprint (m^3/ton) will reduce. As a result of increased production, less needs to be produced elsewhere, releasing the claims on land and (green or blue) water resources elsewhere. Reducing the green water footprint per ton of crop in one place can thus result in a reduction of the blue water footprint in crop production as a whole.
Reduce blue water footprint in crop growth
• Shift to an irrigation technique with lower evaporation loss.
• Choose another crop or crop variety that better fits the regional climate, so needs less irrigation water.
• Increase blue water productivity (ton/m^3) instead of maximising land productivity (yield, ton/ha).
• Improve the irrigation schedule, i.e. optimise timing and volumes of application.
• Irrigate less (deficit irrigation) or not at all.
• Reduce evaporation losses from water storage in reservoirs and from the water distribution system.
Reduce grey water footprint in crop growth
• Apply less or no chemicals (artificial fertilisers, pesticides), e.g. organic farming.
• Apply fertilisers or compost in a form that allows easy uptake, so leaching is reduced.
• Optimise the timing and technique of adding chemicals, so that less is needed and/or less leaches or runs off.

5.5. Investors – water risk mitigation and corporate social responsibility

Not explicitly addressing the water footprint of a business and formulating appropriate response (see the previous section) may translate in various sorts of business risk (Levinson et al., 2008; Morrison et al., 2009; Pegram et al., 2009). First of all, there is the physical risk that companies may face: freshwater shortage affecting their supply chain or own operations. Second, the corporate image of a company may be damaged in a situation where questions are raised among the public and in the media about whether the company properly addresses issues of sustainable and equitable water use. Problems of water depletion or pollution in the supply-chain or operations of a company and the lack of mitigating strategies constitute a reputational risk for a company. Third, triggered by the wish to achieve a more sustainable and equitable use of scarce freshwater resources, governmental interference and regulation in the area of water use will undoubtedly increase. Uncertainty about future regulatory control constitutes a risk for companies that they can better anticipate than ignore. Each of the three above-mentioned sorts of risk may translate to a financial risk in terms of increased

costs and/or reduced revenues. Hence investors are becoming more and more interested in the disclosure of information on the water-related risks of the business they invest in.

Risks can actually turn into an opportunity for those companies that proactively respond to the challenge of global freshwater scarcity. Frontrunners that create product transparency before others do, that formulate specific and measurable targets with respect to water footprint reduction, with special attention to areas where problems of water scarcity and pollution are most critical, and that can demonstrate actual improvements, can turn this into a competitive advantage.

Finally, apart from the need to address risks and the opportunity to profit from a proactive strategy, addressing the issues of freshwater scarcity and pollution should be seen as part of the corporate social responsibility. Currently, environmental concerns in companies are mostly related to energy issues. Expanding the attention towards the field of freshwater is a matter of logic in a world where freshwater scarcity is generally mentioned as the other big environmental challenge next to global warming.

5.6. Governments – national and river basin water policy & international cooperation

Traditionally countries formulate national water plans by looking how to satisfy water users. Even though countries nowadays consider options to reduce water demand in addition to options to increase supply, they generally do not include the global dimension of water management. In this way they do not explicitly consider options to save water through import of water-intensive products. In addition, by looking only at water use in the own country, most governments have a blind spot to the issue of sustainability of national consumption. As a matter of fact many countries have significantly externalized their water footprint without looking whether the imported products are related to water depletion or pollution in the producing countries. Governments can and should engage with consumers and businesses to work towards sustainable consumer products. National water footprint accounting should be a standard component in national water statistics and provide a basis to formulate a national water plan and river basin plans that are coherent with national policies with respect to the environment, agriculture, energy, trade, foreign affairs and development cooperation.

Water footprint and virtual water trade accounts can form a relevant input into the formulation of various sorts of governmental policy: national or state water policy, river basin policy, environmental policy, agricultural policy, energy policy, trade policy, foreign policy and development cooperation policy (Table 5.3). Since the governmental organisation can be regarded as a business in itself, another important thing for governments is to look at the possibility of reducing its own water footprint.

Table 5.3. Options for governments to reduce water footprints and mitigate related impacts.

National water and river basin policy • Adopt the national water footprint accounting scheme to broaden the knowledge base for making well-informed decisions. Use information on water footprints and virtual water trade to support the formulation of both national water plans and river basin plans. • For national water saving: decrease the virtual water export, increase the virtual water import and reduce the water footprint within the nation. • For reducing national water dependency: reduce the external water footprint. • Increase the water use efficiency at the user level, in all sectors, by promoting techniques that enlarge water productivities. • Increase the water use efficiency at the river basin level by allocating water resources to the purposes with highest societal benefit. • Apply the available domestic water resources such that the country produces goods for which it has a comparative advantage relative to other countries.
National environmental policy • For sustainable production: reduce the water footprint within the nation; focus on hotspots where impacts are largest. • For sustainable consumption: reduce the internal and external water footprint of national consumption; focus on hotspots.
National agricultural policy • Do not subsidise water-intensive agriculture in water-scarce areas. • Promote crops that are suitable and adapted to the local climate in order to reduce irrigation demand. • Support investments in irrigation systems and techniques that conserve water. • Promote farmers to avoid or reduce the use of fertilisers, pesticides and insecticides or to better apply so that less chemicals reach the water system.
National energy policy • Study the implications of energy scenarios for water demand. • Harmonise water and energy policies so that energy policies do not increase the water footprint of the energy sector and that water policies do not increase the energy use and carbon footprint of the water sector.
National trade policy • Reduce export of low-value water-intensive products from water-scarce areas (and increase import). • Promote an international water pricing protocol.
National foreign and development cooperation policy • Promote an international agreement on world-wide water footprint reduction. • Promote an international agreement on product transparency. • Cooperate with governments and other agents in developing countries to reduce water footprints; focus on hotspots in the world where water scarcity and pollution problems are most severe and where the nation contributes through its own external water footprint.
Reduce the water footprint of the own governmental organisation and services • See the options provided for business, Table 5.1.
Engaging with consumers and civil society organisations • Awareness raising
Engaging with business • Promote product transparency. Implement by means of voluntary agreements by sector or by legislation. • Translate national targets on water footprint reduction to specific reduction targets for products, producers and/or sectors. Implement through legislation and/or economic incentives (water footprint tax, and/or subsidies to specific water footprint reduction measures).
Engaging with farmers • Promote water footprint reduction in agriculture – see Table 5.2. This can be done in various alternative or complementary ways: regulation or legislation (e.g. on timing, volumes and techniques of irrigation and on application of chemicals), water use licenses, quota, full-cost water pricing, tradable water use permits, and/or subsidies for specific irrigation techniques.

6. Future challenges

6.1. Water footprint assessment methodology and data

There are quite a number of practical issues that one will encounter when carrying out a water footprint assessment. In many cases this manual will give sufficient guidance, but in some other cases there is an obvious need for further development of practical guidelines. A major question will often be how to handle the lack of required data. What default data to use under such circumstances and what simplifications can be reasonably made? A major challenge is therefore to develop more detailed guidelines on what default data can be used when accurate local estimates are not available. In this context it is relevant to develop a database with default water footprint estimates for a large variety of processes and products, differentiating between production regions (e.g. countries). This would be very helpful for assessing the water footprints of consumers or producers, who know what they buy but often do not know all relevant details on the production and supply chain of the things they buy.

A practical issue in water footprint accounting is the truncation problem, which was already discussed in Section 2.2. The question is here: what should be included and what can be excluded from the analysis. By applying a very broad scope of analysis when estimating the water footprint of a specific product, one will discover that some ingredients will not significantly contribute to the overall water footprint of the product and that a continued further tracing of the supply chain does not yield additional value at some point. More practical experience with water footprint accounting for a variety of products is necessary in order to be able to develop practical guidelines on what can – as a rule – be excluded from a product water footprint analysis. And also: what consumer products or input products can be excluded from a consumer or business water footprint analysis, respectively.

An issue that has received no serious attention yet is how to handle variability and change in time. Not all, but many sorts of water use vary over the years, think for instance about the use of irrigation water in agriculture that depends on the rainfall pattern in a specific year. Besides, water productivity may vary from year to year, due to all sorts of factors (including factors that have nothing to do with water), resulting in a variability of the water footprint over the years. Obviously, in this way, changes in a water footprint from one year to another cannot simply be interpreted as a structural improvement or worsening in water use. For that reason, water footprint data will often show a more meaningful picture if they show averages over a period of years. The questions arises what can best be taken as a period of analysis: five years, ten, or even more? When will it be possible to analyse a trend in time? Besides, it will possibly appear that some sorts of input data can be best taken over a very long period (e.g. thirty years as usual for climate data), while other sorts of data can be taken per year or as an average over five years only. It would be useful to develop guidelines in this respect, acknowledging that in the end choices will also depend on the purpose of an analysis.

Related to the issue of variability, but even broader is the issue of uncertainties. The uncertainties in data used in water footprint accounting can be very significant, which means that outcomes should be carefully interpreted.

Carrying out an uncertainty analysis is very much advisable, but often time restrictions will not allow for a very advanced uncertainty and sensitivity analysis. It would be useful to have at least some rough indications that tell the order of magnitude of uncertainties in various sorts of water footprint accounts, so that one could refer to that. Currently, no uncertainty studies are available.

In terms of detail in water footprint accounting, one may find the distinction between a green, blue and grey water footprint too coarse. If desired, one can therefore split up blue water footprint accounts, for example in surface-water footprint, renewable-groundwater footprint and fossil-groundwater footprint accounts (see Section 3.2.1). The grey water footprint can be split up into pollutant-specific grey water footprint accounts (see Section 3.2.3). Another issue is that one may like to distinguish rainwater harvesting as a specific source. The question here is whether consumptive use of this harvested rainwater would fall under the green or blue water footprint. Often, rainwater harvesting refers to the local collection of runoff, which therefore is blue water. But in some cases, like in the case of rainwater harvesting on rooftops, one may argue that it still counts as green water.

In case of the grey water footprint, a challenge is to develop guidelines on how to define natural and maximum allowable concentrations. Both should ideally be catchment-specific, but in many cases such data are not available. Guidelines could advise to use a zero natural background for a specified list of chemicals and recommend which assumptions to make in case of other chemicals when catchment-specific values are not available. Besides, an issue to be cleared is whether one should take for example daily or monthly average concentrations. Maximum allowable concentrations for ambient water quality are not available for all substances; in these cases guidelines should be available to advise what default values can best be used.

A question when measuring the blue water footprint is what resolution and scale can best be applied. What to do when water is withdrawn from one place and returned to another place downstream? According to the definition, the blue water footprint refers to 'consumptive water use', which refers to evapotranspiration, incorporation into a product, or to water that does not return to the same catchment area from which it was withdrawn. It obviously depends on the scale of analysis whether a return flow downstream of the withdrawal is consumptive or not. There may be cases of doubt, where very locally the water is regarded as consumptive but where at a larger scale it returns and thus is non-consumptive. Where to draw the line is something that needs to be found out in due course of time when more studies have been done and a good argument for a certain best scale can be made. Another question is: what to do when groundwater is withdrawn and after use returned to fresh surface water? When blue water – referring to both ground- and surface water – is considered as one category, this sort of interference will not be reflected in the blue water footprint. This is not a problem for many purposes, but in some specific cases it may be desirable to distinguish a blue groundwater footprint and a blue surface water footprint.

Finally, the chapter on water footprint sustainability assessment has shown that any impact investigation is strongly dependent on choices made with respect to which sort of impacts to include and which ones to exclude from the assessment. The current manual provides little guidance on what impacts should be considered at least

and which ones may be of secondary importance. The manual is more like a checklist of impacts that can possibly be considered and shows how each of them could be analysed. It may be desirable to develop more guidance on what sorts of impacts to include depending on the purpose of the analysis.

6.2. Embedding the water footprint in existing water and environmental accounts and reports

Traditional statistics on water use – whether national or corporate accounts – are mostly restricted to water withdrawals. The information basis is very narrow in this way, because it ignores green and grey water use and disregards indirect use as well. In the case of business accounts, the traditional approach pays no attention to water consumption and pollution in the supply chain. In the case of national accounts, the conventional approach overlooks virtual water imports and exports and the fact that part of the water footprint of national consumption lies outside the country. It will be necessary to gradually start incorporating water footprint statistics in governmental statistics and have them feature also in international statistics such as made available through for example the FAO (AQUASTAT, FAOSTAT), the UNEP (Geo Data Portal), the UNDP, the UNCTAD, the UN Statistics Division, the European Commission (Eurostat) and the World Bank. National water footprint statistics were already included in the WWF Living Planet Report (WWF, 2008). In the case of companies, it will be needed to start incorporating water footprint accounts in corporate environmental and sustainability reporting.

6.3. Linking to ecological, energy and carbon footprint methods

The water footprint is part of a family of footprint concepts. The oldest footprint concept is the ecological footprint, introduced in the 1990s by William Rees and Mathis Wackernagel (Rees, 1992; 1996; Rees and Wackernagel, 1994; Wackernagel and Rees, 1996). The ecological footprint measures the use of available bioproductive space and is measured in hectares. The carbon footprint concept originates from the ecological footprint discussion and has started to become more widely known since 2005 (Safire, 2008). The carbon footprint refers to the sum of greenhouse gas emissions caused by an organization, event or product and is expressed in terms of CO_2 equivalents. Although the carbon footprint concept is relatively young, the idea of accounting greenhouse gas emissions is already much older; the first assessment of the Intergovernmental Panel on Climate Change for example already dates back to 1990. Older than the ecological and carbon footprint concepts are also the concepts of 'embodied energy' and 'emergy' as applied in energy studies (Odum, 1996; Herendeen, 2004). These concepts refer to the total energy used to produce a product and are expressed in Joules.

The water footprint was introduced in the field of water studies in the year 2002 (Hoekstra, 2003). The term was chosen by analogy with the ecological footprint concept, but the roots of the water footprint are in water studies rather than environmental studies. Although the concepts of ecological footprint, water footprint, carbon footprint and embodied energy are thus very much related concepts, each of them has its own specific roots. As a result, the methods to quantify the different indicators show both striking similarities and differences. Two

differences between the ecological and the water footprint are for example that ecological footprints are most of the time calculated based on global average productivities, while water footprints are calculated based on local productivities, and that ecological footprints are often not made spatially explicit, while water footprints are (Hoekstra, 2009).

The various 'footprint' concepts are to be regarded as complementary indicators of natural capital use in relation to human consumption. None of the indicators can substitute the other one, simply because each one provides another piece of information. Looking at only area requirements or only water or energy requirements is insufficient, since available land can be a critical factor in development, but available freshwater and energy as well. A challenge for future research is to bring the various footprint concepts and related methods together in one consistent conceptual and analytical framework.

6.4. Linking to material flow analysis, input-output modelling, and life cycle assessment

Material flow analysis (MFA) is a method of analyzing the flows of materials in a well-defined system. On a national or regional scale, MFA can be used to study the material exchanges within an economy and between an economy and the natural environment. In industries, MFA can be used to analyse the material flows within a company or along an industrial supply chain involving a number of companies. When applied to a specific product, MFA refers to the study of inputs (resources) and outputs (emissions) along the different steps in the production system of a product. The latter sort of material flow analysis is similar to what is called the 'inventory phase' of life cycle assessment (LCA). LCA is the investigation and evaluation of the environmental impacts of a given product or service and consists of four phases: goal and scope, life cycle inventory, life cycle impact assessment and interpretation (Rebitzer et al., 2004).

Frameworks like MFA, LCA and input-output modelling consider the use of various types of environmental resources and look at the various types of impacts on the environment. In contrast, ecological-footprint, water-footprint, carbon-footprint and embodied-energy analyses take the perspective of one particular resource or impact. Although it seems logic that 'footprints' are precisely the indicators typically used in MFA, LCA and input-output studies, the methods applied in footprint studies and the methods applied in MFA, LCA and input-output studies do not form one coherent framework of methods. Hitherto, from a water perspective, MFA, LCA and input-output studies do not include freshwater in a sufficient way.

In the input-output research community, there is an increasing interest to include water, see for instance Dietzenbacher and Velazquez (2007) and Zhao et al. (2009). Also within the LCA community there is an increasing interest in water (Koehler, 2008; Milà i Canals et al., 2009). The water footprint has been recognised as a potential useful concept in LCA, but has been criticised for the absence of 'characterization factors' to weigh water volumes consumed based on their impact. Some LCA authors have suggested redefining the water footprint from a volumetric measure to an index that results from multiplying volumes by impact factors (Pfister et al., 2009; Ridoutt et al., 2009). It has also been proposed to neglect green water footprints, because impacts

would be nil (Pfister and Hellweg, 2009). Framing their argument within the logic of LCA, these authors do not capture the primary and established role of the water footprint in the field of water resources management (WRM). Redefining the water footprint does not make sense from a WRM perspective, which requires spatially and temporally explicit information on water footprints in real volumes and impacts in real terms as well.

Water footprint studies serve two discourses in water resources management. First, data on water footprints of products, consumers, and producers inform the discourse about sustainable, equitable, and efficient freshwater use and allocation. Freshwater is scarce; its annual availability is limited. It is relevant to know who receives which portion and how water is allocated over various purposes. For example, rainwater used for bioenergy cannot be utilized for food. Second, water footprint accounts help to estimate environmental, social, and economic impacts at local and catchment level. Environmental impact assessment should include a comparison of each water footprint component to available water at relevant locations and time (accounting for environmental water requirements).

The call for weighing different water footprint components based on their relative (local) environmental impact is justified from an LCA perspective. To serve both WRM and LCA, one best distinguishes three steps (Table 6.1). From an LCA viewpoint, the first step contributes to life-cycle inventory; the second and third steps are part of lifecycle impact assessment. The proposal to use the term water footprint for the final aggregated index obtained in the third step is confusing. This may be instrumental for LCA but not helpful for other purposes. The water footprint can best be used solely in its original and well-established meaning, which means it excludes impact. The non-volumetric index obtained in the third step is not a water footprint, but an aggregated, weighed water footprint impact index (see Box 4.4).

Table 6.1. How water footprint assessment can feed LCA.

Water footprint assessment phase	Outcome	Physical meaning	Resolution	LCA phase
Water footprint accounting	Blue, green and grey water footprints (volumetric)	Water volume consumed or polluted per unit of product	Spatiotemporally explicit	Life cycle inventory
Water footprint sustainability assessment	An evaluation of the sustainability of a water footprint at micro-, meso- and macro-level, from environmental, social and economic perspective	Various measurable impact variables	Spatiotemporally explicit	Life cycle impact assessment
Aggregation of selected information from the water foot-print sustainability assessment	Aggregated water footprint impact indices	None	Non spatiotemporally explicit	

Source: based on Hoekstra et al. (2009a).

7. Conclusion

The water footprint, introduced in 2002, is a young concept and water footprint assessment is a method still in development. The current manual gives the state-of-the art. The part that presents the method of water footprint accounting is, after seven years of continued development, more or less established. Nevertheless, various challenges remain, including the development of practical guidelines per product category and business sector on how to truncate the analysis (where to stop going back along supply-chains) and rules on how to account for uncertainties and how to deal with time variability when doing trend analysis. Besides, there is a huge challenge to develop databases on typical process water footprints (the basic ingredient for each analysis) and tools to make it easier for practitioners to set up a water footprint account. Following the guidelines on water footprint accounting as provided in this manual is much more labour-intensive than when one could use a simple computer tool guiding the analysis. Developing such a tool together with underlying databases is therefore part of the work programme of the Water Footprint Network.

The chapters on water footprint sustainability assessment and policy response options are less mature than the chapter on water footprint accounting. This is due to the fact that these two phases of water footprint assessment have got less attention so far, both in scientific studies and in practical implementation. The current manual is mainly limited to categorising the various impacts and responses that could be considered. At this stage it is a reference framework for impacts and response options rather than an in-depth treatment of how specific types of impacts can be elaborated and studied in more detail or how specific response options can be studied in more detail in terms of their implications and strengths and weaknesses.

The broad interest in the water footprint concept and methodology has taken off in September 2007 with a small meeting between representatives from civil society, business, academia and the UNESCO-IHE Institute for Water Education. Since then the interest in applying the water footprint in governmental policy and corporate strategy has been growing continuously. This has led to the establishment of the Water Footprint Network on 16 October 2008. Precisely twelve months later, the network had 76 partners, coming from all continents and from all sorts of sectors: government, business, investors, civil society, intergovernmental institutions, consultants, universities and research institutes. A major challenge is to develop a shared language in the field of water footprint assessment, because concrete targets towards sustainable water resources use can only be transparent, meaningful and effective when formulated in a common terminology and based on a shared calculation methodology. This water footprint manual aims to provide a step towards such a common base. Adjustments and refinement to the manual will be made in the future based on new research and development and on experiences from practitioners working with the method in their own practice.

Literature

Alcamo, J., and Henrichs, T. (2002) Critical regions: A model-based estimation of world water resources sensitive to global changes, Aquatic Sciences 64(4): 352-362.

Aldaya, M.M. and Hoekstra, A.Y. (2009) The water needed to have Italians eat pasta and pizza, Value of Water Research Report Series No. 36, UNESCO-IHE, Delft, the Netherlands, www.waterfootprint.org/Reports/Report36-WaterFootprint-Pasta-Pizza.pdf.

Aldaya, M.M. and Llamas, M.R. (2008) Water footprint analysis for the Guadiana river basin, Value of Water Research Report Series No. 35, UNESCO-IHE, Delft, the Netherlands, www.waterfootprint.org/Reports/Report35-WaterFootprint-Guadiana.pdf.

Aldaya, M.M., Garrido, A., Llamas, M.R., Varelo-Ortega, C., Novo, P., and Casado, R.R. (2010) Water footprint and virtual water trade in Spain, In: A. Garrido and M.R. Llamas (eds.), Water policy in Spain, CRC Press, Leiden, The Netherlands, pp. 49-59.

Allan, J.A. (1998) Virtual water: A strategic resource, global solutions to regional deficits, Groundwater 36(4), 545-546.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop evapotranspiration - Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization, Rome, Italy.

Batjes, N.H. (2006) ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid, Report 2006/02, ISRIC – World Soil Information, Wageningen, The Netherlands, available through www.isric.org.

Brown, B.J., Hanson, M.E., Liverman, D.M., Merideth R.W. (1987) Global sustainability: toward definition, Environmental Management 11 (6): 713-719.

Bulsink, F., Hoekstra, A.Y. and Booij, M.J. (2009) The water footprint of Indonesian provinces related to the consumption of crop products, Value of Water Research Report Series No. 37, UNESCO-IHE, Delft, the Netherlands, www.waterfootprint.org/Reports/Report37-WaterFootprint-Indonesia.pdf.

Chapagain, A.K. and Hoekstra, A.Y. (2004) Water footprints of nations, Value of Water Research Report Series No. 16, UNESCO-IHE, Delft, the Netherlands, www.waterfootprint.org/Reports/Report16Vol1.pdf.

Chapagain, A.K., and Hoekstra, A.Y. (2007) The water footprint of coffee and tea consumption in the Netherlands, Ecological Economics 64(1): 109-118.

Chapagain, A.K. and Hoekstra, A.Y. (2008) The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products, Water International 33(1): 19-32.

Chapagain, A.K., Hoekstra, A.Y., and Savenije, H.H.G. (2006a) Water saving through international trade of agricultural products, Hydrology and Earth System Sciences 10(3): 455-468.

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G. and Gautam, R. (2006b) The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries, Ecological Economics 60(1): 186-203.

Chapagain, A. K. and S. Orr (2008) UK Water Footprint: The impact of the UK's food and fibre consumption on global water resources, WWF-UK, Godalming, UK.

Chapagain, A.K., and Orr, S. (2009) An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes, Journal of Environmental Management 90: 1219-1228.

Clark, G.M., Mueller, D.K., Mast, M.A. (2000) Nutrient concentrations and yields in undeveloped stream basins of the United States, Journal of the American Water Resources Association 36(4): 849-860.

CropLife Foundation (2006) National pesticide use database 2002, CropLife Foundation, Washington, D.C., USA, www.croplifefoundation.org/cpri_npud2002.htm.

Dabrowski, J.M., Murray, K., Ashton, P.J. and Leaner, J.J. (2009) Agricultural impacts on water quality and implications for virtual water trading decisions, Ecological Economics 68(4): 1074-1082.

Dastane, N.G. (1978) Effective rainfall in irrigated agriculture, Irrigation and Drainage Paper No.25, Food and Agriculture Organization, Rome, Italy, www.fao.org/docrep/X5560E/x5560e00.htm#Contents.

Dietzenbacher, E. and Velazquez, E. (2007) Analysing Andalusian virtual water trade in an input - output framework, Regional Studies 41(2): 185-196.

Dominguez-Faus, R., Powers, S.E., Burken, J.G. and Alvarez, P.J. (2009) The water footprint of biofuels: A drink or drive issue? Environmental Science & Technology 43(9): 3005-3010.

EPA (2005) List of drinking water contaminants: ground water and drinking water, US Environmental Protection Agency, www.epa.gov/safewater/mcl.html#1

EU (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, European Union, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0060:20090113:EN:PDF

EU (2006) Directive 2006/44/EC of the European Parliament and of the Council of 6 September 2006 on the quality of fresh waters needing protection or improvement in order to support fish life, European Union, Brussels, Belgium, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:264:0020:0031:EN:pdf

Eurostat (2007) The use of plant protection products in the European Union: Data 1992-2003, Eurostat Statistical Books, European Commission, http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-76-06-669/EN/KS-76-06-669-EN.PDF.

Falkenmark, M. (1989) The massive water scarcity now threatening Africa: Why isn't it being addressed? Ambio 18(2): 112-118.

Falkenmark, M. (2003) Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges, Philosophical Transaction of the Royal Society of London B 358(1440): 2037-2049.

Falkenmark, M. and Rockström, J. (2004) Balancing water for humans and nature: The new approach in ecohydrology, Earthscan, London, UK.

FAO (2003) Technical conversion factors for agricultural commodities, Food and Agriculture Organization, Rome, Italy, www.fao.org/fileadmin/templates/ess/documents/methodology/tcf.pdf.

FAO (2005) New LocClim, Local Climate Estimator CD-ROM, Food and Agriculture Organization, Rome, Italy, www.fao.org/nr/climpag/pub/en3_051002_en.asp.

FAO (2009a) CLIMWAT 2.0 database, Food and Agriculture Organization, Rome, Italy, www.fao.org/nr/water/infores_databases_climwat.html.

FAO (2009b) CROPWAT 8.0 model, Food and Agriculture Organization, Rome, Italy, www.fao.org/nr/water/infores_databases_cropwat.html.

FAO (2009c) FertiStat database, Food and Agriculture Organization, Rome, Italy, www.fao.org/ag/agl/fertistat.

FAO (2009d) FAOSTAT database, Food and Agriculture Organization, Rome, Italy, http://faostat.fao.org.

FAO (2009e) AQUASTAT database, Food and Agriculture Organization, Rome, Italy, www.fao.org/nr/water/aquastat/main/index.stm.

FAO (2009f) Global Information and Early Warning System (GIEWS), Food and Agriculture Organization, Rome, Italy, www.fao.org/giews/countrybrief/index.jsp, www.fao.org/giews/workstation/data.

FAO (2009g) Global map of monthly reference evapotranspiration and precipitation – at 10 arc minutes, GeoNetwork grid database, www.fao.org/geonetwork/srv/en.

FAO (2009h) Global map maximum soil moisture – at 5 arc minutes, GeoNetwork grid database, www.fao.org/geonetwork/srv/en.

Galloway, J.N., Burke, M., Bradford, G.E., Naylor, R., Falcon, W., Chapagain, A.K., Gaskell, J.C., McCullough, E., Mooney, H.A., Oleson, K.L.L., Steinfeld, H., Wassenaar, T. and Smil, V. (2007) International trade in meat: The tip of the pork chop, Ambio 36(8): 622-629.

Garrido, A., Llamas, M.R., Varela-Ortega, C., Novo, P., Rodríguez-Casado, R. and Aldaya, M.M. (2009) Water footprint and virtual water trade in Spain, Springer, New York, USA.

Gerbens-Leenes, P.W. and Hoekstra, A.Y. (2009) The water footprint of sweeteners and bio-ethanol from sugar cane, sugar beet and maize, Value of Water Research Report Series No. 38, UNESCO-IHE, Delft, the Netherlands.

Gerbens-Leenes, P.W., Hoekstra, A.Y. and Van der Meer. Th. (2009a) The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply, Ecological Economics 68(4): 1052-1060.

Gerbens-Leenes, W., Hoekstra, A.Y. and Van der Meer, T.H. (2009b) The water footprint of bioenergy, Proceedings of the National Academy of Sciences 106 (25): 10219-10223.

Gerbens-Leenes, W., Hoekstra, A.Y., and Van der Meer, T.H. (2009c) A global estimate of the water footprint of *Jatropha curcas* under limited data availability, Proceedings of the National Academy of Sciences 106(40): E113.

Gleick, P.H. (ed.) (1993) Water in crisis: A guide to the world's fresh water resources, Oxford University Press, Oxford, UK.

Heffer, P. (2009) Assessment of fertilizer use by crop at the global level, International Fertilizer Industry Association, Paris, France, www.fertilizer.org/ifa/Home-Page/LIBRARY/Publication-database.html/Assessment-of-Fertilizer-Use-by-Crop-at-the-Global-Level-2006-07-2007-08.html2

Herendeen, R.A. (2004) Energy analysis and EMERGY analysis - A comparison, Ecological Modelling 178: 227-237.

Hoekstra, A.Y. (ed.) (2003) Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade, Delft, The Netherlands, 12-13 December 2002, Value of Water Research Report Series No.12, UNESCO-IHE, Delft, The Netherlands, www.waterfootprint.org/Reports/Report12.pdf.

Hoekstra, A.Y. (2008a) Water neutral: reducing and offsetting the impacts of water footprints, Value of Water Research Report Series No.28, UNESCO-IHE, Delft, The Netherlands, www.waterfootprint.org/Reports/Report28-WaterNeutral.pdf.

Hoekstra, A.Y. (2008b) The relation between international trade and water resources management, In: K.P. Gallagher (ed.) Handbook on trade and the environment, Edward Elgar Publishing, Cheltenham, UK, pp. 116-125.

Hoekstra, A.Y. (2008c) The water footprint of food, In: Förare, J. (ed.) Water for food, The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), Stockholm, Sweden, pp. 49-60.

Hoekstra, A.Y. (2009) Human appropriation of natural capital: A comparison of ecological footprint and water footprint analysis, Ecological Economics 68(7): 1963-1974.

Hoekstra, A.Y. and Chapagain, A.K. (2007a) Water footprints of nations: water use by people as a function of their consumption pattern, Water Resources Management. 21(1): 35-48.

Hoekstra, A.Y. and Chapagain, A.K. (2007b) The water footprints of Morocco and the Netherlands: Global water use as a result of domestic consumption of agricultural commodities, Ecological Economics 64(1): 143-151.

Hoekstra, A.Y. and Chapagain, A.K. (2008) Globalization of water: Sharing the planet's freshwater resources, Blackwell Publishing, Oxford, UK.

Hoekstra, A.Y., Gerbens-Leenes, W. and Van der Meer, T.H. (2009a) Water footprint accounting, impact assessment, and life-cycle assessment, Proceedings of the National Academy of Sciences 106(40): E114.

Hoekstra, A.Y., Gerbens-Leenes, W. and Van der Meer, T.H. (2009b) The water footprint of *Jatropha curcas* under poor growing conditions, Proceedings of the National Academy of Sciences 106(42): E119.

Hoekstra, A.Y. and Hung, P.Q. (2005) Globalisation of water resources: international virtual water flows in relation to crop trade, Global Environmental Change 15(1): 45-56.

Hubacek, K., Guan, D.B., Barrett, J. and Wiedmann, T. (2009) Environmental implications of urbanization and lifestyle change in China: Ecological and water footprints, Journal of Cleaner Production, 17(14): 1241-1248.

Humbert, S., Loerincik, Y., Rossi, V., Margnia, M. and Jolliet, O. (2009) Life cycle assessment of spray dried soluble coffee and comparison with alternatives (drip filter and capsule espresso), Journal of Cleaner Production 17(15): 1351-1358.

IFA (2009) IFA data, International Fertilizer Industry Association, www.fertilizer.org/ifa/ifadata/search.

Jongschaap, R.E.E., Blesgraaf, R.A.R., Bogaard, T.A., Van Loo, E.N. and Savenije, H.H.G. (2009) The water footprint of bioenergy from Jatropha curcas L., Proceedings of the National Academy of Sciences 106(35): E92-E92.

Kitzes, J. (ed.) (2009) Ecological footprint standards 2009 Version 3.2, Global Footprint Network, Oakland, CA, USA, www.footprintstandards.org.

Koehler, A. (2008) Water use in LCA: managing the planet's freshwater resources, International Journal of Life Cycle Assessment 13(6): 451-455.

Kumar, V., Jain, S.K. (2007) Status of virtual water trade from India, Current Science 93: 1093-1099.

Levinson, M. et al. (2008) Watching water: A guide to evaluating corporate risks in a thirsty world, JPMorgan, USA.

Liu, J. and Savenije, H.H.G. (2008) Food consumption patterns and their effect on water requirement in China, Hydrology and Earth System Sciences 12(3): 887-898.

Liu, J.G., Williams, J.R., Zehnder, A.J.B., Yang, H. (2007) GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale, Agricultural Systems 94(2): 478-493.

Ma, J., Hoekstra, A.Y., Wang, H., Chapagain, A.K. and Wang, D. (2006) Virtual versus real water transfers within China, Phil. Trans. R. Soc. Lond. B. 361 (1469): 835-842.

MacDonald, D.D., Berger, T., Wood, K., Brown, J., Johnsen, T., Haines, M.L., Brydges, K., MacDonald, M.J., Smith, S.L. and Shaw. D.P. (2000) Compendium of environmental quality benchmarks, MacDonald Environmental Sciences, Nanaimo, British Columbia, Canada, www.pyr.ec.gc.ca/georgiabasin/reports/Environmental%20Benchmarks/GB-99-01_E.pdf.

Maes, W.H., Achten, W.M.J. and Muys, B. (2009) Use of inadequate data and methodological errors lead to an overestimation of the water footprint of Jatropha curcas, Proceedings of the National Academy of Sciences, 106(34): E91-E91.

MAPA (2001) Calendario de siembra, recolección y comercialización, años 1996-1998. Spanish Ministry of Agriculture, Madrid, 656 p.

MARM (2009) Agro-alimentary Statistics Yearbook. Spanish Ministry of the Environment and Rural and Marine Affairs [online] Available from: http://www.mapa.es/es/estadistica/pags/anuario/introduccion.htm.

Milà i Canals, L., Chenoweth, J., Chapagain, A., Orr, S., Antón, A. and Clift, R. (2009) Assessing freshwater use impacts in LCA: Part I—inventory modelling and characterisation factors for the main impact pathways, Journal of Life Cycle Assessment 14(1) 28-42.

Mitchell, T.D. and Jones, P.D. (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids, International Journal of Climatology, 25, 693-712, http://cru.csi.cgiar.org/continent_selection.asp.

Monfreda, C., Ramankutty, N., Foley, J.A. (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000, Global Biogeochemical Cycles, 22(1): GB1022, www.geog.mcgill.ca/landuse/pub/Data/175crops2000.

Morrison, J., Morkawa, M., Murphy, M., and Schulte, P. (2009) Water scarcity and climate change: Growing risks for business and investors, CERES, Boston, MA, USA.

NASS (2009) Agricultural chemical use database, National Agricultural Statistics Service, www.pestmanagement.info/nass.

Nazer, D.W., Siebel, M.A., Van der Zaag, P., Mimi, Z. and Gijzen, H.J. (2008) Water footprint of the Palestinians in the West Bank, Journal of the American Water Resources Association 44(2): 449-458.

NCDC (2009) Global surface summary of the day, National Climatic Data Center, www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html, data available from ftp://ftp.ncdc.noaa.gov/pub/data/gsod.

Novo, P., Garrido, A. and Varela-Ortega, C. (2009) Are virtual water "flows" in Spanish grain trade consistent with relative water scarcity? Ecological Economics 68(5): 1454-1464.

Odum, H.T. (1996) Environmental accounting: Emergy and environmental decision making, Wiley, New York.

Pegram, G., Orr, S., and Williams, C. (2009) Investigating shared risk in water: Corporate engagement with the public policy process, WWF, Godalming, UK.

Pfister, S., Hellweg, S. (2009) The water "shoesize" vs. footprint of bioenergy, Proceedings of the National Academy of Sciences 106(35): E93-E94.

Pfister, S., Koehler, A. and Hellweg, S. (2009) Assessing the environmental impacts of freshwater consumption in LCA, Environmental Science and Technology 43: 4098-4104.

Poff, N.L., Richter, B.D., Aarthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keeffe, J.H., D.Olden, J., Rogers, K., Tharme, R.E. and Warner, A. (2009) The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards, Freshwater Biology, doi:10.1111/j.1365-2427.2009.02204.x.

Portmann, F., Siebert, S., Bauer, C. and Dll, P. (2008) Global data set of monthly growing areas of 26 irrigated crops. Frankfurt Hydrology Paper 06, Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html.

Portmann, F.T., Siebert, S. and Döll P. (2009) MIRCA2000 - Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, Global Biogeochemical Cycles, doi:10.1029/2008GB003435.

Postel, S.L., Daily, G.C., and Ehrlich, P.R. (1996) Human appropriation of renewable fresh water, Science 271: 785-788.

Raskin, P.D., E. Hansen and R.M. Margolis (1996) Water and sustainability: global patterns and long-range problems, Natural Resources Forum 20(1): 1-5.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P. and Pennington, D.W. (2004) Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications, Environment International 30: 701-720.

Rees, W.E. (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out, Environment and Urbanization 4(2): 121-130.

Rees, W.E. (1996) Revisiting carrying capacity: Area-based indicators of sustainability, Population and Environment 17(3): 195-215.

Rees, W.E. and Wackernagel, M. (1994) Ecological footprints and appropriated carrying capacity: Measuring the natural capital requirements of the human economy, In: Jansson, A.M., Hammer, M., Folke, and Costanza, R. (eds.) Investing in natural capital: The ecological economics approach to sustainability, Island Press, Washington, D.C., pp. 362-390.

Richter, B.D. (2009) Re-thinking environmental flows: from allocations and reserves to sustainability boundaries, River Research and Applications, DOI: 10.1002/rra.1320.

Ridoutt, B.G., Eady, S.J., Sellahewa, J., Simons, L. and Bektash, R. (2009) Water footprinting at the product brand level: case study and future challenges, Journal of Cleaner Production 17(13): 1228-1235.

Rockström, J. (2001) Green water security for the food makers of tomorrow: windows of opportunity in drought-prone savannahs Water Science and Technology 43 (4): 71-78.

SABMiller and WWF-UK (2009) Water footprinting: Identifying & addressing water risks in the value chain, SABMiller, Woking, UK / WWF-UK, Goldalming, UK.

Safire, W. (2008) On language: Footprint, New York Times, February 17, 2008.

Siebert, S., Döll, P., Feick, S., Hoogeveen, J. and Frenken, K. (2007) Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany / Food and Agriculture Organization, Rome, Italy, www.fao.org/nr/water/aquastat/irrigationmap/index10.stm.

Smakhtin, V., Revenga, C., and Döll, P. (2004a) Taking into account environmental water requirements in global-scale water resources assessments Comprehensive Assessment Research Report 2, IWMI, Colombo, Sri Lanka.

Smakhtin, V., Revenga, C. and Döll, P. (2004b) A pilot global assessment of environmental water requirements and scarcity, Water International 29(3): 307-317.

Smith, M. (1992) CROPWAT – A computer program for irrigation planning and management, Irrigation and Drainage Paper 46, FAO, Rome, Italy.

Smith, R.A., Alexander, R.., Schwarz, G.E. (2003) Natural background concentrations of nutrients in streams and rivers of the conterminous United States, Environmental Science and Technology 37(14): 3039-3047.

Sonnenberg, A., Chapagain, A., Geiger, M. and August, D. (2009). Der Wasser-Fußabdruck Deutschlands: Woher stammt das Wasser, das in unseren Lebensmitteln steckt? WWF Deutschland, Frankfurt.

UNEP (2009) GEMSTAT, Global water quality data and statistics, Global Environment Monitoring System, UNEP, Nairobi, www.gemstat.org.

USDA (1994) The major world crop areas and climatic profiles, Agricultural Handbook No. 664, World Agricultural Outlook Board, United States Department of Agriculture, www.usda.gov/oce/weather/pubs/Other/MWCACP/MajorWorldCropAreas.pdf

Van der Leeden, F., Troise, F.L. and Todd, D.K. (1990) The water encyclopedia, Second edition, CRC Press, Boca Raton, Florida, USA.

Van Oel, P.R., Mekonnen M.M. and Hoekstra, A.Y. (2009) The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment, Ecological Economics 69(1): 82-92.

Verma, S., Kampman, D.A., Van der Zaag, P. and Hoekstra, A.Y. (2009) Going against the flow: A critical analysis of inter-state virtual water trade in the context of India's National River Linking Programme, Physics and Chemistry of the Earth 34: 261-269.

Wackernagel, M. and Rees, W. (1996) Our ecological footprint: Reducing human impact on the earth New Society Publishers, Gabriola Island, B.C., Canada.

Wichelns, D. (2004) The policy relevance of virtual water can be enhanced by considering comparative advantages, Agricultural Water Management 66(1): 49-63.

Wiedmann, T.O., Lenzen, M., Barrett, J.R. (2009) Companies on the scale comparing and benchmarking the sustainability performance of businesses, Journal of Industrial Ecology 13(3): 361-383.

Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A. (1989) The EPIC crop growth-model, Transactions of the ASAE 32(2): 497–511.

Williams, J.R. (1995) The EPIC model, In: Singh, V.P. (ed.) Computer models of watershed hydrology, Water Resources Publisher, Colorado, USA, pp. 909–1000.

WRI and WBCSD (2004) The greenhouse gas protocol: A corporate accounting and reporting standard, Revised edition, World Resources Institute, Washington, DC and World Business Council for Sustainable Development, Conches-Geneva, www.ghgprotocol.org/files/ghg-protocol-revised.pdf.

WWAP (2009) The United Nations World Water Development Report 3: Water in a changing world, World Water Assessment Programme, UNESCO Publishing, Paris / Earthscan, London.

WWF (2008) Living planet report 2008, WWF International, Gland, Switzerland.

Yang, H., Zhou, Y., Liu, J.G. (2009) Land and water requirements of biofuel and implications for food supply and the environment in China, Energy Policy 37(5): 1876-1885.

Zhao, X., Chen, B., Yang, Z.F. (2009) National water footprint in an input-output framework - A case study of China 2002, Ecological Modelling 220(2): 245-253.

Appendix I: Calculating the process water footprint of growing a crop – an example for sugar beet in Valladolid (Spain)

This appendix provides an example of how to estimate the green, blue and grey process water footprints of growing a crop. It focuses on the case of a sugar beet (*Beta vulgaris var. vulgaris*) production in a one-hectare irrigated crop field in Valladolid (north-central Spain).

Green and blue components of the process water footprint

First, the green-blue water evapotranspiration has been estimated using the CROPWAT 8.0 model (Allen et al., 1998; FAO, 2009b). There are two different ways to do this: using the crop water requirement option (assuming optimal conditions) or the irrigation schedule option (including the possibility to specify actual irrigation supply in time). A comprehensive manual for the practical use of the program is available online (FAO, 2009b).

In both cases the calculations have been done using climate data from the nearest and most representative meteorological station located in the crop-producing region (Figure I.1). When possible, crop data were obtained from local agricultural research stations. The planting dates at provincial level were obtained from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 2001) (Table I.1). In the temperate north of Spain, beets are planted in the spring and harvested in the autumn. In warmer southern areas (Andalusia), sugarbeets are a winter crop, planted in the autumn and harvested in the spring. Crop coefficients and crop lengths according to the type of region and climate were taken from FAO (Allen et al., 1998, Tables 11 and 12). Data on rooting depth, critical depletion level and yield response factor were obtained from FAO global databases (FAO, 2009b). Besides, in the irrigation schedule option, soil data are required to estimate the soil water balance. Soil information was also obtained from FAO (2009b).
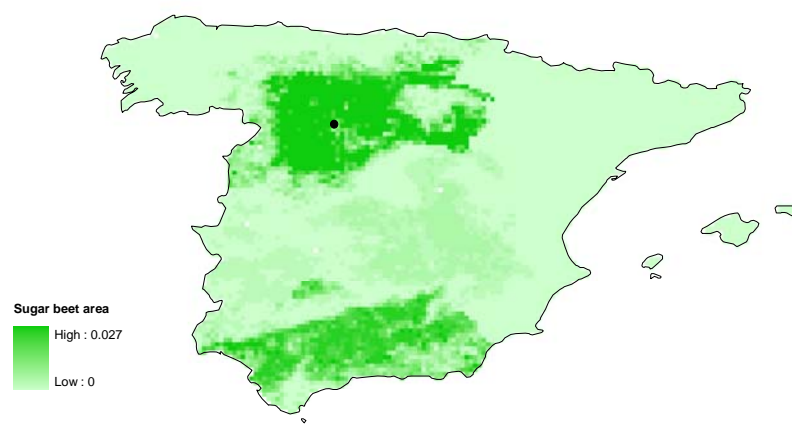
Figure I.1. *Climate station in Valladolid (Spain) (dot in black) and sugar beet harvested area in Spain (unit: proportion of grid cell area). Source of sugar beet area: Monfreda et al. (2008).*

Table I.1. *Planting and harvesting dates and yield for sugar beet production in Valladolid (Spain).*

Crop	Planting date*	Harvesting date*	Yield (ton/ha)**
Sugar beet	1 April (March-April)	27 Sept (Sept-Oct)	81

* Source: MAPA (2001)

** Source: MARM (2009) period 2000-2006

*Table I.2.*Total green-blue water evapotranspiration based on the CWR output table of CROPWAT 8.0.

Month	Period	Stage	K_c	ET_c	ET_c	P_{eff}	Irr. req.	ET_{green}	ET_{blue}
			-	mm/day	mm/period	mm/period	mm/period	mm/period	mm/period
Apr	1	Init	0.35	1.02	10.2	12.6	0	10.2	0
Apr	2	Init	0.35	1.13	11.3	13.8	0	11.3	0
Apr	3	Init	0.35	1.24	12.4	14	0	12.4	0
May	1	Init	0.35	1.35	13.5	14.5	0	13.5	0
May	2	Init	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	Late	1.23	7.39	73.9	3.3	70.6	3.3	70.6
Aug	3	Late	1.13	6.05	66.6	5.7	60.9	5.7	60.9
Sep	1	Late	1	4.65	46.5	8.9	37.5	8.9	37.6
Sep	2	Late	0.87	3.51	35.1	11.2	23.8	11.2	23.9
Sep	3	Late	0.76	2.6	18.2	7.8	7	7.8	10.4
Over the total growing period					796	176	625	168	628

1. Crop water requirement option

This option estimates evapotranspiration under optimal conditions, which means that crop evapotranspiration (ET_c) equals the crop water requirement (*CWR*). Optimal means 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 can be run with climate and crop data alone. ET_c is estimated with a ten day time-step and over the total growing season using the effective rainfall. To calculate the effective rainfall, the USDA SCS (USDA Soil Conservation Service) was chosen as it is one of the most widely used methods. The model calculates ET_c as follows:

$$ET_c = K_c \times ET_o$$

Here, K_c refers to the crop coefficient, which incorporates crop characteristics and averaged effects of evaporation from the soil. ET_o represents the reference evapotranspiration, which expresses the evapotranspiration from a hypothetical grass reference crop not short of water.

The green water evapotranspiration (ET_{green}) is calculated as the minimum of total crop evapotranspiration (ET_c) and effective rainfall (P_{eff}), with a time step of ten days. The total green water evapotranspiration is obtained by summing up ET_{green} over the growing period. The blue water evapotranspiration (ET_{blue}) is estimated as the difference between the total crop evapotranspiration (ET_c) and the total effective rainfall (P_{eff}) on a ten-day basis. When the effective rainfall is greater than the crop total crop evapotranspiration ET_{blue} is equal to zero. The total blue water evapotranspiration is obtained by adding ET_{blue} over the whole growing period (Table I.2).

$$ET_{green} = \min\left(ET_c, P_{eff}\right)$$

$$ET_{blue} = \max\left(0, ET_c - P_{eff}\right)$$

2. Irrigation schedule option

In the second option we can calculate the crop evapotranspiration under both optimal and non-optimal conditions over the total growing season using the daily soil water balance approach. The calculated evapotranspiration is called ET_a, the adjusted crop evapotranspiration. ET_a may 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 can be influenced by different factors, such as physical condition, fertility and biological status of the soil. ET_a is calculated using a water stress coefficient (K_s):

$$ET_a = K_s \times ET_c = K_s \times K_c \times ET_o$$

K_s describes the effect of water stress on crop transpiration. For soil water limiting conditions, $K_s < 1$; when there is no soil water stress, $K_s = 1$.

The irrigation schedule option requires climate, crop and soil data. To estimate the green water evapotranspiration (ET_{green}) the 'no irrigation (rain-fed)' choice is selected within the 'Options' button on the Toolbar (Table I.3). Under this scenario:

$$ET_{green}\left(irr = 0\right) = ET_a\left(irr = 0\right)$$

$$ET_{blue}\left(irr = 0\right) = 0$$

To estimate the blue water evapotranspiration, different irrigation timing and application options can be selected depending on the actual irrigation strategy. The default option, 'irrigate at critical depletion' and 'refill soil to field capacity', assumes "optimal" irrigation where the irrigation intervals are at a maximum whilst avoiding any crop stress. The average irrigation application depth per irrigation is related to the irrigation method practised. Generally, in the case of high frequency irrigation systems, such as micro-irrigation and centre pivot, about 10 mm or less per wetting event are applied. In the case of surface or sprinkler irrigation, irrigation depths are 40 mm or more. In the sugar beet production in Valladolid 40 mm are applied every 7 days (Table I.4). After running the model with the selected irrigation options, the blue water evapotranspiration (ET_{blue}) is estimated as

Table I.3. *Irrigation schedule under the rain-fed scenario - output table of CROPWAT 8.0.*

CROP IRRIGATION SCHEDULE

ETo station: VALLADOLID   Crop: Sugar beet   Planting date: 01/04

Rain station: VALLADOLID   Soil: Medium (loam)   Harvest date: 27/09

Yield red.: 50.1 %

Crop scheduling options

Timing: No irrigation (rain-fed)

Application: -

Field eff.   70 %

Table format: Daily soil moisture balance

Date	Day	Stage	Rain	K_s	ET_a	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	-	mm	%	mm	mm	mm	mm	l/s/ha
01-Apr	1	Init	0	1	1	1	0	1	0	0	0
02-Apr	2	Init	0	1	1	2	0	2	0	0	0
03-Apr	3	Init	6.7	1	1	1	0	1	0	0	0
04-Apr	4	Init	0	1	1	2	0	2	0	0	0
05-Apr	5	Init	0	1	1	3	0	3	0	0	0
06-Apr	6	Init	0	1	1	4	0	4.1	0	0	0
07-Apr	7	Init	6.7	1	1	1	0	1	0	0	0
08-Apr	8	Init	0	1	1	2	0	2	0	0	0
09-Apr	9	Init	0	1	1	3	0	3	0	0	0
10-Apr	10	Init	0	1	1	4	0	4.1	0	0	0
11-Apr	11	Init	0	1	1.1	5	0	5.2	0	0	0
12-Apr	12	Init	0	1	1.1	6	0	6.3	0	0	0
13-Apr	13	Init	7.4	1	1.1	1	0	1.1	0	0	0
…											
25-Sep	178	End	0	0.21	0.5	92	0	266.5	0	0	0
26-Sep	179	End	0	0.2	0.5	92	0	267	0	0	0
27-Sep	End	End	0	0.2	0	90					

Totals:

Total gross irrigation	0	mm		Total rainfall	190.3	mm
Total net irrigation	0	mm		Effective rainfall	171.1	mm
Total irrigation losses	0	mm		Total rain loss	19.3	mm
Actual water use by crop	432.2	mm		Moist deficit at harvest	261.1	mm
Potential water use by crop	793.3	mm		Actual irrigation requirement	622.3	mm
Efficiency irrigation schedule	-	%		Efficiency rain	89.9	%
Deficiency irrigation schedule	45.5	%				

Yield reductions:

Stage label	A	B	C	D	Season	
Reductions in ET_c	0	0	53.3	87.7	45.5	%
Yield response factor	0.5	0.8	1.2	1	1.1	
Yield reduction	0	0	64	87.7	50.1	%
Cumulative yield reduction	0	0	64	95.6		%

Table I.4. *Irrigation schedule under the irrigation scenario - output table of CROPWAT 8.0.*

CROP IRRIGATION SCHEDULE

ETo station: VALLADOLID Crop: Sugar beet Planting date: 01/04

Rain station: VALLADOLID Soil: Medium (loam) Harvest date: 27/09

Yield red.: 0.0 %

Crop scheduling options

Timing: Irrigate at user defined intervals

Application: Fixed application depth of 40 mm

Field eff. 70 %

Table format: Daily soil moisture balance

Date	Day	Stage	Rain	K_s	ET_a	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	-	mm	%	mm	mm	mm	mm	l/s/ha
01-Apr	1	Init	0	1	1	1	0	1	0	0	0
02-Apr	2	Init	0	1	1	2	0	2	0	0	0
03-Apr	3	Init	6.7	1	1	1	0	1	0	0	0
04-Apr	4	Init	0	1	1	2	0	2	0	0	0
05-Apr	5	Init	0	1	1	3	0	3	0	0	0
06-Apr	6	Init	0	1	1	4	0	4.1	0	0	0
07-Apr	7	Init	6.7	1	1	1	40	0	39	57.1	6.61
08-Apr	8	Init	0	1	1	1	0	1	0	0	0
09-Apr	9	Init	0	1	1	2	0	2	0	0	0
10-Apr	10	Init	0	1	1	3	0	3	0	0	0
11-Apr	11	Init	0	1	1.1	4	0	4.2	0	0	0
12-Apr	12	Init	0	1	1.1	5	0	5.3	0	0	0
13-Apr	13	Init	7.4	1	1.1	1	0	1.1	0	0	0
…											
25-Sep	178	End	0	1	2.6	6	0	16.3	0	0	0
26-Sep	179	End	0	1	2.6	7	0	18.9	0	0	0
27-Sep	End	End	0	1	0	4					

Totals:

Total gross irrigation	1428.6	mm	Total rainfall	190.3	mm
Total net irrigation	1000.0	mm	Effective rainfall	125.1	mm
Total irrigation losses	344.8	mm	Total rain loss	65.2	mm
Actual water use by crop	793.3	mm	Moist deficit at harvest	13.0	mm
Potential water use by crop	793.3	mm	Actual irrigation requirement	668.3	mm
Efficiency irrigation schedule	65.5	%	Efficiency rain	65.7	%
Deficiency irrigation schedule	0.0	%			

Yield reductions:

Stage label	A	B	C	D	Season	
Reductions in ET_c	0	0	0	0	0	%
Yield response factor	0.5	0.8	1.2	1	1.1	
Yield reduction	0	0	0	0	0	%
Cumulative yield reduction	0	0	0	0		%

the difference between the total crop evapotranspiration (ET_a) under the irrigation scenario and the green water evapotranspiration (ET_{green}) as previously found in the rain-fed scenario.

$$ET_{green}(irr=1) = ET_{green}(irr=0)$$

$$ET_{blue}(irr=1) = ET_a(irr=1) - ET_{green}(irr=1)$$

In both options (CWR and irrigation schedule), the estimated crop evapotranspiration in mm is converted to m³/ha applying the factor 10. The green component in the process water footprint of a crop ($WF_{proc,green}$, m³/ton) is calculated as the green component in crop water use (CWU_{green}, m³/ha) divided by the crop yield Y (ton/ha). The blue component ($WF_{proc,blue}$, m³/ton) is calculated in a similar way:

$$WF_{proc,green} = \frac{CWU_{green}}{Y}$$

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y}$$

The outcome of both options is given in Table I.5. The results are similar with respect to the total ET and the resultant total water footprint, but quite different with respect to the ratio blue/green. In the irrigation schedule option, it appears that there is much lower irrigation requirement.

Table I.5. *Calculation of the green and blue components of the process water footprint (m³/ton) for sugar beet in Valladolid (Spain) using the CWR-option and irrigation schedule option for a medium soil.*

CROPWAT option	ET_{green}	ET_{blue}	ET_{tot}	CWU_{green}	CWU_{blue}	CWU_{tot}	$Y*$	$WF_{proc,green}$	$WF_{proc,blue}$	WF_{proc}
	mm / growing period			m³/ha			ton/ha	m³/ton		
Crop water requirement option	168	628	796	1680	6280	7960	81	21	78	98
Irrigation schedule option	432	361	793	4320	3610	7930	81	53	45	98

* Source: MARM (2009) period 2000-2006

The calculations above refer to the evapotranspiration from the field; we have not yet accounted for the green and blue water incorporated into the harvested crop. The water fraction of sugar beet is in the range of 75-80%, which means that the water footprint of sugar beet is 0.75-0.80 m³/ton if we look at incorporated water alone. This is less than 1 percent of the water footprint related to evaporated water.

Grey component in the process water footprint

The grey component in the process water footprint of a primary crop (m³/ton) is calculated as the load of pollutants that enters the water system (kg/yr) divided by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration c_{max}) and its natural concentration in the

receiving water body (c_{nat}) (Table I.6). The quantity of nitrogen that reaches free flowing water bodies has been assumed to be 10 percent of the applied fertilization rate (in kg/ha/yr) (Hoekstra and Chapagain, 2008). The effect of the use of other nutrients, pesticides and herbicides to the environment has not been analyzed. The total volume of water required per ton of N is calculated considering the volume of nitrogen leached (ton/ton) and the maximum allowable concentration in the free flowing surface water bodies. By absence of local ambient water quality standards for nitrogen, we have used the standard recommended by the US EPA for nitrate in water: 10 mg/litre (measured as N). This limit was used to calculate the volume of freshwater required to assimilate the load of pollutants. By lack of appropriate data, the natural concentration in the receiving water body was assumed to be zero. Data on the application of fertilizers have been obtained from the FertiStat database (FAO, 2009c).

Table I.6. Calculation of the grey component of the process water footprint (m^3/ton) for sugar beet in Valladolid (Spain).

Average fertilizer application rate*	Area	Total fertilizer applied	Nitrogen leached to water bodies 10%	US EPA (2009)	Total $WF_{proc,grey}$ sugar beet	Production**	$WF_{proc,grey}$ sugar beet
kg/ha	ha	ton/year	ton/year	mg/l	10^6 m^3/year	ton	m^3/ton
178	1	0.2	0.02	10	0.002	81	22

*Source: FertiStat (FAO, 2009c)

**Source: MARM (2009) period 2000-2006

Appendix II: Calculating the water footprint of a product – example for refined sugar from Valladolid (Spain)

This appendix provides an example of how to estimate the green, blue and grey water footprint of a product focusing on the case of the refined sugar production from Valladolid (Spain).

If a primary crop is processed into a crop product (e.g. sugar beet processed into raw sugar), there is often a loss of weight, because only part of the primary product is used. The water footprint of crop products is calculated by dividing the water footprint of the input product by the product fraction. The product fraction is defined as the quantity of the output product obtained per quantity of input product. The product fractions for various crop products are derived from different commodity trees as defined in FAO (2003) and Chapagain and Hoekstra (2004). Figure II.1 gives the product tree for refined sugar. If the input product is processed into two or more different products, one needs to distribute the water footprint of the input product across its separate products. This is done proportionally to the value of the input products. The value fraction for a processed product is defined as the ratio of the market value of the output product to the aggregated market value of all the output products obtained from the input product. If during processing there is some water use involved, the process water use is added to the water footprint value of the root product before the total is distributed over the various processed products.
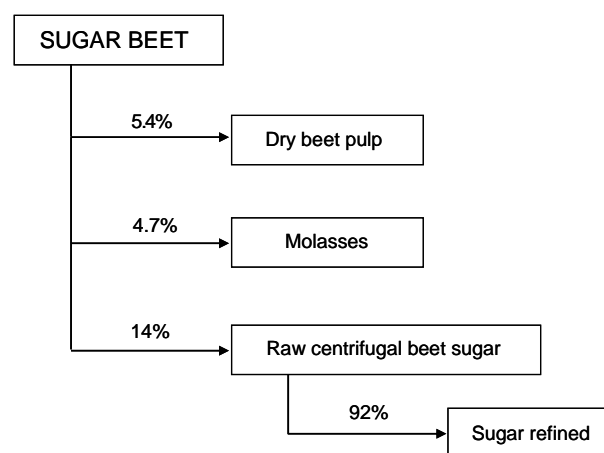
Figure II.1. *Spanish refined sugar production (from sugar beet) diagram including product fractions. Source: Own elaboration based on FAO (2003).*

The sugar beet naturally contains sugar. In a sugar production plant this sugar is removed from the beet and converted into granulated sugar. The beet harvest begins in mid-September. Most of the beet is delivered by truck. The beet delivered is first washed in water in large washing units. The water used is cleaned in the water purification plant for reuse. The soil that is removed is first stored in storage fields and subsequently used to raise dikes, for example. The clean beet is then sliced in cutting machines. The sugar in these beet strips is removed in diffusion towers with warm water. The result is raw juice with a sugar concentration of 14% (FAO, 2003). This is almost the same amount as in the beet itself. The extracted beet strips, now called pulp, are

pressed or dried and sold as animal fodder. The following stage in the production process is the purification of the raw juice. The raw juice is purified into thin juice with lime and carbon dioxide (CO_2). Lime and CO_2 are produced on the premises of the production plant in a lime oven from limestone and cokes. The lime absorbs all unwanted substances and this precipitates through the addition of CO_2. This solid matter is filtered off. It is a powerful, natural lime fertiliser that improves the structure of the soil and it is sold under the name Betacal SU. As the water evaporates the thin juice gradually becomes thick juice with a sugar content of approximately 70%. Finally, so much water evaporates in the "vacuum pans" that a saturated solution is obtained. Subsequently the crystallisation process begins by adding fine sugar crystals that serve as seed material. By continuing to evaporate the water, these sugar crystals gradually develop to the required size. In centrifuges the crystal-clear sugar crystals are separated from the liquid (syrup) and, after drying, the sugar is stored in large silos. The syrup is called molasses and it serves as the raw material for the production of alcohol.

Sugar industry co-products are shown in the production diagram in Figure II.1. Beet pulp is dried and sold via the feed ingredient industry to dairy farmers who use dried pulp or store pressed pulp in silos and use the silage for milk and meat production. Pulp is also sold to farmers with sows where it has a positive influence on environmental problems, as the dry matter content of manure produced by the sows is higher, and the ammonia level in the pig house is lower. Experiments are also being done to feed sugar beet pulp to fattening pigs with promising results. The sugar industry molasses is sold to the alcohol industry and the co-product of this alcohol industry (vinasses) is used in the dairy feed industry with a small part now used by farmers as a potassium fertilizer.

During the process described above, the use of water is limited as much as possible. The sugar factories use especially water from the beets. This is released in the production process as a condensate of evaporation. Sugar beets contain more than 75% of water. During the sugar production, thus, a surplus of water arises originating from the sugar beets (ibid.). After purification, this water becomes drained into surface water. During the washing of the beets organic matter comes into the washing water and is purified. Besides aerobic purification, anaerobic purification also takes place in the methane engines, in which durable biogas is produced.

The water footprint of refined sugar has been estimated separately for the green, blue and grey components. This has been done in two steps: first for the intermediate raw centrifugal beet sugar and second for the refined sugar.

First, the green water footprint of raw centrifugal beet sugar is estimated following the equation:

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

As described above the process water footprint ($WF_{proc}[p]$) is equal to zero. The green water footprint of the input sugar beet ($WF_{prod}[i]$) produced in Valladolid (Spain) amounts to about 53 m^3/ton (Appendix I). The

100

product fraction ($f_p[p,i]$) in line with the sugar production diagram is 0.14 ton/ton. And the value fraction ($f_v[p]$) amounts to about 0.89 US$/US$ calculated as follows:

$$f_v[p] = \frac{price[p] \times w[p]}{\sum\limits_{p=1}^{z} \left(price[p] \times w[p] \right)}$$

$$f_v[p] = \frac{price_{rawcentr.beetsugar} \times weight_{rawcentr.beetsugar}}{price_{drybeetpulp} \times w_{drybeetpulp} + price_{molasses} \times w_{molasses} + price_{rawcentr.beetsugar} \times w_{rawcentr.beetsugar}}$$

All in all the green water footprint of raw centrifugal beet sugar adds up to 337 m^3/ton.

Second, the green water footprint of refined sugar is calculated. Here again the process water footprint ($WF_{proc}[p]$) is equal to zero. The green water footprint of the input raw centrifugal beet sugar ($WF_{prod}[i]$) is 337 m^3/ton. The product fraction ($f_p[p,i]$) in line with the sugar production diagram is 0.92 ton/ton and the value fraction ($f_v[p]$) is 1 US$/US$ since there is just one output product. Finally the green water footprint of refined sugar produced in Valladolid (Spain) is 366 m^3/ton. The blue and grey water footprint are calculated in a similar way (Table II.1).

Table II.1. *Green, blue and grey water footprint for sugar beet in Valladolid (Spain) (m^3/ton).*

Process water footprint of sugar beet crop (m^3/ton)				Product water footprint of refined sugar (m^3/ton)			
$WF_{proc,green}$	$WF_{proc,blue}$	$WF_{proc,grey}$	WF_{total}	$WF_{proc,green}$	$WF_{proc,blue}$	$WF_{proc,grey}$	WF_{total}
53	45	22	120	366	311	152	829

Appendix III: Environmental flow requirements

In the framework of water footprint discussions it is crucial to have standards on environmental flow requirements. When we are interested in the environmental impacts of the blue water footprint (consumptive water use of runoff), it is crucial to know the environmental flow requirements in the catchment where the blue water footprint is located. Runoff in a catchment (R) minus environmental flow requirements (EFR) is what is available for human use. Blue water availability (WA_{blue}) is thus defined as:

$$WA_{blue} = R - EFR$$

The blue water footprint (WF_{blue}) in a catchment needs to be compared to WA_{blue}. When WF_{blue} approaches or exceeds WA_{blue} there is a reason for concern. We know R for many catchments in the world and if no empirical data are available we have model estimates. The time resolution is sometimes daily, but at least we generally know R on a monthly basis. Water footprint data have so far mostly been presented on an annual basis, but behind those estimates is always information about its course over time, because water footprint calculations are based on irrigation water use calculations with a time step of 1 to 10 days. Comparing WF_{blue} to WA_{blue} can be done on an annual basis, but that is very crude and insensitive to what actually happens throughout the year, so it is better to make this comparison on for example a monthly basis. There is sufficient literature to conclude that establishing EFR in a particular catchment will always be an elaborate job. It is tempting to have a simple, generic, easily applicable standard on estimating EFR, so that one can easily assess the environmental impact of a blue water footprint in an arbitrary catchment in the world. The broad literature on environmental flow requirements provides many useful methods, guidelines and examples, but there is only one worldwide study on environmental flow requirements based on a simple rule and readily available data: the study by Smakhtin et al. (2004a,b). The good thing about this study is that it offers what many practitioners want (easy method, clear numbers, world-coverage); the Smakhtin-map frequently features in business reports and presentations. The downside is that the method gives annual instead of monthly values for EFR and that many experts do not agree with the calculation rules, parameters used and the resultant EFR estimates. According to Brian Richter of The Nature Conservancy the Smakhtin-method greatly underestimates environmental flow requirements (personal communication, 2009).

For practical purpose it is proposed here to work towards a simple (based on readily available data) and generic (worldwide applicable) method to establish environmental flow requirements for catchments with a low temporal resolution but high enough to capture the main variations within a year. The estimates obtained with this method can function as default EFR estimates in cases where more advanced estimates are not yet available. It should be stressed that the simple generic method would give first estimates only, to be replaced by better estimates when possible. For that purpose one could rely for example on the ELOHA framework for establishing environmental flow requirements, an advanced framework being proposed by some of world's top experts in this field (Poff et al., 2009). This method is money and labour intensive, so it will take at least several years before we will have a worldwide coverage of EFR estimates based on this approach.

For the time being, the following simple generic rule for establishing environmental flow requirements is proposed:

1. For each month of the year, the mean monthly runoff in developed condition is in a range ±20% of the mean monthly flow as would happen under undeveloped condition, and
2. For each month of the year, the mean monthly base flow is in a range ±20% of the mean monthly base flow as would happen under undeveloped condition.

Mean monthly flows are often available through river flow measurements, and if not we can use model estimates. The term 'base flow' refers to the groundwater contribution to a river, which can be estimated based on for instance a 10-year river flow record.

In order to create more detail it is proposed to distinguish 'levels of river basin modification'. Referring to the deviation (Δ) of the mean monthly flows under developed condition to those under undeveloped conditions, the following scheme can be used:

$\Delta < \pm 20\%$	unmodified or slightly modified	river status A
$\pm 20\% < \Delta < \pm 30\%$	moderately modified	river status B
$\pm 20\% < \Delta < \pm 40\%$	significantly modified	river status C
$\Delta > \pm 40\%$	seriously modified	river status D

Today, how many basins will fall in the four categories A to D? The majority of non-dam-regulated rivers will fall in status A. The dam-regulated rivers will fall in categories B-D. The 20% rule is regarded as a 'precautionary default *EFR*'. The above boundaries can be called 'thresholds for potential concern'. This terminology better reflects the fact that the above boundaries are indicative rather than decisive.

The appropriate spatial scale for establishing *EFR* is the catchment level. *EFR* at river basin level can be derived as the sum of *EFR* values of the catchments that together constitute the river basin. Given that *EFR* can best be expressed at catchment level, ideally the water footprint is specified at that detail as well. Ideally, water footprint accounting is done in a spatial explicity way using a geographic information system (GIS), so in that case one can always localise the water footprint rather precise.

The local impact of a blue water footprint in a river can be quantified by counting the (average) number of months in a year that the environmental flow requirements in the river are not met and by considering the degree to which the environmental flow requirements are violated. It is not said that the blue water footprint of the activity considered is fully responsible for the violation of the environmental flow requirements, because it is the sum of the blue water footprints of all activities that result in violation. Therefore one can also look at the relative contribution of the activity considered. A blue water footprint of a certain activity at a certain spot forms a 'hotspot' when (a) the blue water footprint at that spot related to the activity is substantial relative to the total

blue water footprint at the spot, and (b) the blue water footprint contributes to violation of environmental flow requirements during a certain period of the year.

The above simple method is based on initial thoughts from some water resource experts (personal communication between Jay O'Keeffe, UNESCO-IHE; Brian Richter, TNC; Stuart Orr, WWF; Arjen Hoekstra, University of Twente). We need agreement among and support from the broad community of EFR experts on this simple generic method, because undoubtedly the method will be criticised, which is understandable given both the diverse interests (environment versus water users) and the scientific difficulty to translate the actual complexity towards simple rules. However, possible criticism has not withhold experts from setting simple toxicity and water quality standards, so why would it withhold us from establishing *EFR* standards. Quantifying environmental flow requirements is essential to be able to let them count in assessing the impacts of blue water consumption.

Appendix IV: Frequently asked questions

Practical questions

1. Why should we bother about our water footprint?

Freshwater is a scarce resource; its annual availability is limited and demand is growing. The water footprint of humanity has exceeded sustainable levels at several places and is unequally distributed among people. Good information about water footprints of communities and businesses will help to understand how we can achieve a more sustainable and equitable use of fresh water. There are many spots in the world where serious water depletion or pollution takes place: rivers running dry, dropping lake and groundwater levels and endangered species because of contaminated water. The water footprint helps to show the link that exists between our daily consumption of goods and the problems of water depletion and pollution that exist elsewhere, in the regions where our goods are produced. Nearly every product has a smaller or larger water footprint, which is of interest for both consumers that buy those products and businesses that produce, process, trade or sell those products in some stage of their supply chain.

2. Why should my business bother about its water footprint?

First of all, environmental awareness and strategy is often part of what a business regards as its 'corporate social responsibility'. Reducing the water footprint can be part of the environmental strategy of a business, just like reducing the carbon footprint. Second, many businesses actually face serious risks related to freshwater shortage in their operations or supply chain. What is a brewery without secure water supply or how can a company in jeans survive without continued supply of water to the cotton fields? A third reason to do water footprint accounting and formulate measures to reduce the corporate water footprint is to anticipate regulatory control by governments. In the current stage it is not so clear how governments will respond, but obviously regulations in some sectors of business may be expected. Finally, some businesses see a corporate water footprint strategy also as an instrument to reinforce the corporate image or to strengthen the brand name.

3. What can consumers do to reduce their water footprint?

Consumers can reduce their *direct* water footprint (home water use) by installing water saving toilets, applying a water-saving showerhead, closing the tap during teeth brushing, using less water in the garden and by not disposing medicines, paints or other pollutants through the sink. The *indirect* water footprint of a consumer is generally much larger than the direct one. A consumer has basically two options to reduce his/her indirect water footprint. One option is to substitute a consumer product that has a large water footprint by a different type of product that has a smaller water footprint. Examples: eat less meat or become vegetarian, drink tea instead of coffee, or even better drink plain water. Not wearing cotton but artificial fibre clothes saves a lot of water. But this approach has limitations, because many people don't easily shift from meat to vegetarian and people like their coffee and cotton. A second option is to stick to the same consumption pattern but to select the cotton, beef or coffee that has a relatively low water footprint or that has its footprint in an area that doesn't have high water scarcity. This requires, however, that consumers have proper information to make that choice. Since this information is generally not available in the world of today, an important thing consumers can do now is ask

product transparency from businesses and regulation from governments. When information is available on the impacts of a certain article on the water system, consumers can make conscious choices about what they buy.

4. What can businesses do to reduce their water footprint?

Businesses can reduce their *operational* water footprint by saving water in their own operations and bringing water pollution to zero. Keywords are: avoid, reduce, recycle and treat before disposal. For most businesses, however, the *supply-chain* water footprint is much larger than the operational footprint. It is therefore crucial that businesses address that as well. Achieving improvements in the supply chain may be more difficult – because not under direct control – but they may be more effective. Businesses can reduce their supply-chain water footprint by making supply agreements with certain standards with their suppliers or by simply changing to another supplier. In many cases it probably means quite something, because the whole business model may need to be transformed in order to incorporate or better control supply chains and to make supply chains fully transparent to consumers. Among the various alternative or supplementary tools that can help improving transparency are: setting quantitative water-footprint reduction targets, benchmarking, product labelling, certification and water footprint reporting.

5. Why should governments make national water footprint accounts?

Traditionally, countries formulate national water plans by looking how to satisfy water users. Even though countries nowadays consider options to reduce water demand in addition to options to increase supply, they generally do not include the global dimension of water management. In this way they do not explicitly consider options to save water through import of water-intensive products. In addition, by looking only at water use in the own country, most governments have a blind spot to the issue of sustainability of national consumption. As a matter of fact many countries have significantly externalized their water footprint without looking whether the imported products are related to water depletion or pollution in the producing countries. Governments can and should engage with consumers and businesses to work towards sustainable consumer products. National water footprint accounting should be a standard component in national water statistics and provide a basis to formulate a national water plan and river basin plans that are coherent with national policies with respect to the environment, agriculture, energy, trade, foreign affairs and development cooperation.

6. When is my water footprint sustainable?

As a consumer, your water footprint is sustainable when (a) the total remains below your fair share of the available green and blue freshwater resources in the world, and (b) no component of the total water footprint presses at places where or times when local environmental flow requirements or ambient water quality standards are violated.

7. How can I offset my water footprint?

This is a question often posed by people that are familiar with the idea of carbon offsetting. In the case of carbon it does not matter where mitigating measures are taken, so one can offset own CO_2 emissions by helping to reduce CO_2 emissions or enhancing carbon sequestration elsewhere. In the case of water, this is different,

because water depletion or pollution in one place cannot be compensated by whatever measure in another place. The focus should therefore be on reduction of the own water footprint, most urgent at the places where and times when this water footprint causes problems. We should do all that is 'reasonably possible' to reduce the own water footprint, both the direct and indirect one. This holds for both consumers and businesses. Only in second instance, when everything has been done to reduce the own water footprint, one can consider offsetting. This means that the residual water footprint is offset by making a 'reasonable investment' in establishing or supporting projects that aim at a sustainable, equitable and efficient use of water in the catchment where the residual water footprint is located. The terms 'reasonably possible' and 'reasonable investment' include normative elements that need further quantitative specification and about which we need to reach societal consensus.

8. I already pay for the water, isn't that enough?

Generally the price paid for water is far below its real economic cost. Most governments subsidise water supply on a huge scale by investing in infrastructure like dams, canals, distribution systems, and wastewater treatment. These costs are often not charged to the water users. As a result, there is insufficient economic incentive for water users to save water. Besides, due to the public character of water, water scarcity is generally not translated into an additional component in the price of goods and services that are produced with the water, as happens naturally in the case of private goods. Finally, water users generally do not pay for the negative impacts that they cause on downstream people or ecosystems.

9. Is a water footprint always bad?

The water footprint shows the plain volumes of water consumption and pollution, including where and when, in all phases of the supply-chain of a product. This is interesting from both a global and local perspective. The water footprint specifies the total water volume apparently appropriated for a certain product. Since freshwater availability on earth is limited, it is important to know how it is allocated over various purposes, to feed debates such as water for nature versus food, water for food versus energy, or water for basic needs versus luxury goods. Besides, it is interesting to see how water is shared among people. Since overexploitation of fresh water already occurs in many places and global water availability is limited, a reduction of the total water footprint of humanity is fundamental to sustainable development. This is the global perspective. The water footprint can also form the basis for a more detailed impact assessment at catchment level. The water footprint map (showing where and when what volumes of water are being appropriated) is the basis for assessing the local impacts of the various water footprint components. For this purpose the water footprint map can be overlaid with a map showing local water stress. In this way one can identify the hotspots where water footprint reduction is most urgent. Water footprint reduction is thus driven from a global perspective, but in particular cases from a local perspective as well.

10. What are reasonable water footprint reduction targets?

There is no general answer to this question, because it depends on the product, available technology, local context, etc. Besides, one has to keep in mind that the question includes a normative element, which implies that

it needs to be answered in a societal-political context. A few general things can be said, however. First of all, one has to distinguish between reduction targets with respect to the green, blue and grey water footprint. As for the grey water footprint, which refers to water pollution, one can demand a reduction to zero for all products, at least in the long term. Pollution is not necessary. A zero grey water footprint can be achieved by prevention, recycling and treatment. Only thermal pollution (by water use for cooling) is difficult to reduce to zero. The blue water footprint in the agricultural stage of products can often be brought down by a factor two by reduction of consumptive water losses; in the industrial stage it will depend very much on the sector and what has already been done. Technologically, industries can fully recycle water, so that the blue water footprint can everywhere be reduced to the amount of water that is actually being incorporated into the product. Benchmarks can be developed for specific products by taking the performance of the best producers as a reference. Another general rule for any water footprint mitigation strategy is to avoid the water footprint pressing in areas or times where environmental flow requirements are violated. A final rationale for a water footprint mitigation strategy can be the fair sharing of water resources. This may be the basis for water footprint reduction particularly for large water users. Green water footprints in agriculture can often be reduced very substantially by using the green water resources more efficiently, i.e. by increasing the green water productivity. Increased production based on green water resources in one place will reduce the need for production with blue water resources elsewhere.

11. Is the water footprint similar to the carbon footprint?

The two concepts nicely complement each other, each concept addressing another environmental issue: the carbon footprint addresses the issue of climate change, the water footprint relates to the issue of freshwater scarcity. In both cases, a supply-chain perspective is promoted. There are also differences, however. For a carbon emission it doesn't matter where it happens, but for a water footprint is does matter. A carbon emission in one place can be offset by carbon emission reduction or sequestration in another place, which is not true for water: one cannot reduce the local impact of water use in one place by saving water in another place.

12. Freshwater can be obtained by desalinating seawater, so why water is scarce?

Desalination of salt or brackish water can only be a solution for freshwater scarcity in a limited number of applications, not because one cannot obtain the right quality of water for all purposes, but because desalination requires energy, another scarce resource. In fact, desalination is a way of substituting one scarce resource (freshwater) by another one (energy). If at a certain spot the freshwater issue is pressing even more than the energy issue, one can decide in favour of desalination, but in general it doesn't make sense to propose desalination as a general solution to freshwater scarcity. Besides, apart from the energy argument, desalination is still expensive, too expensive for use in agriculture where most of the water is used. Finally, salt or brackish water are only available along coasts, which means that bringing desalinated water elsewhere would imply additional costs (again including energy).

13. Should products get a water label?

In a world where many products are related to water depletion and pollution it is very useful to make the history of products more transparent. It is good to have the facts publicly available, so the consumer has a choice.

Information can be provided on a label or can be made available through internet. This is most useful for products that often have large effects on water, like products that contain cotton or sugar. For consumers it would be helpful to integrate a water label in broader labels that include other issues as well, like energy and fair trade. Ideal would be a world in which we don't need labels because we can trust that all products meet strict criteria. If a water label is considered, the question is what should be on the label? One could put the total water footprint of the product on a label, which is functional only for raising awareness among consumers, not for enabling the consumer to make a well-informed choice between two products. For supporting good product choice, one would also need to specify the green-blue-grey components and mention the degree in which the product's water footprint relates to violation of environmental flow requirements or ambient water quality standards. For example, three quarters of the water footprint is situated in areas where environmental flow requirements or ambient water quality standards are met, but the other quarter of the total water footprint is in areas where those norms are violated. In the end, labelling of products is a partial solution at best. As a means of awareness raising and basis for product choice, it can be functional, but it is just one way of providing product transparency, restricted by the practical problem that a label can contain limited information only. Besides, real water footprint reduction will not occur just by providing information on a label.

Technical questions

1. What is a water footprint?

The water footprint of a product is an empirical indicator of how much water is consumed and polluted, when and where, measured over the whole supply chain of the product. The water footprint is a multidimensional indicator, showing volumes but also making explicit the type of water use (consumptive use of rainwater, surface water or groundwater, or pollution of water) and the location and timing of water use. The water footprint of an individual, community or business, is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business. The water footprint shows human appropriation of the world's limited freshwater resources and thus provides a basis for discussing water allocation and issues that relate to sustainable, equitable and efficient water use. Besides, the water footprint forms a basis for assessing the impacts of goods and services at catchment level and formulating strategies to reduce those impacts.

2. What is new about the water footprint?

Traditionally, statistics on water use focus on measuring 'water withdrawals' and 'direct water use'. The water footprint accounting method takes a much broader perspective. First of all, the water footprint measures both direct and indirect water use, where the latter refers to the water use in the supply chain of a product. The water footprint thus links final consumers and intermediate businesses and traders to the water use along the whole production chain of a product. This is relevant, because generally the direct water use of a consumer is small if compared to its indirect water use and the operational water use of a business is generally small if compared to the supply-chain water use. So the picture of the actual water dependency of a consumer and business can change radically. The water footprint method further differs in that it looks at water consumption (as opposed to

withdrawal), where consumption refers to the part of the water withdrawal that really gets lost through evaporation, i.e. the part of the water withdrawal that does not return to the system from which it was withdrawn. Besides, the water footprint goes beyond looking at blue water use only (i.e. use of ground and surface water). It also includes a green water footprint component (use of rainwater) and a grey water footprint component (polluted water).

3. Is the water footprint more than a nice metaphor?

The term "footprint" is often used as a metaphor to refer to the fact that humanity appropriates a significant proportion of the available natural resources (land, energy, water). However, just like the "ecological footprint" and the "carbon footprint", the "water footprint" is more than a metaphor: there is a rigorous accounting framework with well-defined measurable variables and well-established accounting procedures to calculate the water footprints of products, individual consumers, communities, nations or businesses. We discourage people to use the water-footprint concept as a metaphor, because its strength lies in its effectiveness when used in a context of strict accounting and measurable reduction targets.

4. Water is a renewable resource, it remains in the cycle, so what's the problem?

Water is a renewable resource, but that does not mean that its availability is unlimited. In a certain period, precipitation is always limited to a certain amount. The same holds to the amount of water that recharges groundwater reserves and that flows through a river. Rainwater can be used in agricultural production and water in rivers and aquifers can be used for irrigation or industrial or domestic purposes. But one cannot use more water than is available. One cannot take more from a river than its flow in a certain period and in the long term one cannot take more water from lakes and groundwater reservoirs than the rate with which they are recharged. The water footprint measures the amount of water available in a certain period that is consumed (i.e. evaporated) or polluted. In this way, it provides a measure of the amount of available water appropriated by humans. The remainder is left for nature. The rainwater not used for agricultural production is left to sustain natural vegetation. The ground- and surface water flows not evaporated for human purposes or polluted is left to sustain healthy aquatic ecosystems.

5. Is there agreement on how to measure a water footprint?

The methods for water footprint accounting have been published in peer-reviewed scientific journals. In addition, there are also practical examples available of how one can apply the methods to calculate the water footprint of a specific product, an individual consumer, a community or a business or organisation. In generic sense there is agreement about the definition and calculation of a water footprint. However, every time one applies the concept in a situation not done before, new practical questions arise. These are practical questions like: what should be included and what can be excluded, how to deal with situations where the supply chain cannot be properly traced, what water quality standards to use when calculating the grey water footprint, etc. Discussion therefore focuses on how to handle those practical issues. There is also still discussion about the precise method of how to estimate the local impacts of a water footprint.

6. Why distinguish between a green, blue and grey water footprint?

Freshwater availability on earth is determined by annual precipitation above land. One part of the precipitation evaporates and the other part runs off to the ocean through aquifers and rivers. Both the evaporative flow and the runoff flow can be made productive for human purposes. The evaporative flow can be used for crop growth or left for maintaining natural ecosystems; the green water footprint measures which part of the total evaporative flow is actually appropriated for human purposes. The runoff flow – the water flowing in aquifers and rivers – can be used for all sorts of purposes, including irrigation, washing, processing and cooling. The blue water footprint measures the volume of groundwater and surface water consumed, i.e. withdrawn and then evaporated. The grey water footprint measures the volume of water flow in aquifers and rivers polluted by humans. In this way, the green, blue and grey water footprint measure different sorts of water appropriation. When necessary, one can further classify the water footprint into more specific components. In the case of the blue water footprint, it can be considered relevant to distinguish between ground and surface water use. In the case of the grey water footprint, it can be considered valuable to distinguish between different sorts of pollution. In fact, preferably, this more specific pieces of information are always underlying the aggregate water footprint figures.

7. Why should we look at the total green water footprint of a crop? Why not look at the additional evaporation if compared to evaporation from natural vegetation?

It depends on the question that one would like to address. The green water footprint measures total evaporation and is meant to feed the debate about the allocation of water to different purposes in a context of limited availability. Information about increased or reduced evaporation is relevant from the perspective of catchment hydrology and potential downstream effects. Research has shown that crops can sometimes result in increased evaporation when compared to natural vegetation (particularly in the period of rapid crop growth), and other times in reduced evaporation (e.g. because of soil deterioration or reduced aboveground biomass). In many cases the differences are not very significant at basin scale. The change in evaporation is interesting from the perspective of catchment hydrology and potential downstream effects, but not for the debate on how limited freshwater resources are allocated over different purposes. The water footprint is designed for the latter debate. The purpose of the green water footprint is to measure human's appropriation of the evaporative flow, just like the blue/grey water footprint aims to measure human's appropriation of the runoff flow. The green water footprint measures the part of the evaporated rainwater that has been appropriated by human being and is therefore not available for nature. The water footprint thus expresses the cost of a crop in terms of its total water use.

8. Isn't it too simplistic to add all cubic metres of water used into one aggregate indicator?

The aggregate water footprint of a product, consumer or producer shows the total volume of fresh water consumed or polluted. It serves as a rough indicator, instrumental in raising awareness and for getting an idea of where most of the water goes. The water footprint can be presented as one aggregate number, but in fact it is a multidimensional indicator of water use, showing different sorts of water consumption and pollution as a function of space and time. For developing strategies for sustainable water use, one will need to use the more detailed layer of information embedded in the composite water footprint indicator.

9. Shouldn't we weigh the different water footprint components based on their impact?

The idea of 'weighing factors' sounds like an attractive idea, because not every cubic metre of water used has the same impact. However, we strongly discourage this approach for three reasons. First, weighing is and will always remain very subjective, because there are many different sorts of (environmental, social and economic) impacts, some of which cannot even be easily quantified. Second, impacts are always fully local-context dependent, which means that it is impossible to design universally valid weighing factors. As a matter of fact, the impact of one cubic metre of water withdrawn from one particular point in a river at a certain point in time depends on the characteristics of that river, like the volume and variability of water flow in the river, the competition over water at that point in the river at that particular moment and the effects of withdrawal on downstream ecosystems and other users. Third, weighing would take away the beauty of the current approach, namely that the water footprint figures actually mean something (they refer to actual volumes of water used). In order to properly address the fact that different water footprint components do indeed have different local impacts, we emphasize that the water footprint is a multidimensional indicator, showing volumes, but also the type of water use and the locations and timing of water use. The aggregate water footprint figure is always composed of various components, so that one can precisely tell where and when what type of water is consumed or polluted. 'Water footprint accounting' means that one quantifies the water footprint in all its details. This forms the proper basis for a local impact assessment, in which one assesses the various impacts for each separate water footprint component in time and space. Obviously, the local impact assessment will show that the impact is different for each separate water footprint component. For formulating water policy aimed to reduce water footprint impacts it is more useful to know how different water footprint components link to various impacts than to have a weighed water footprint impact index. The risk of making a seemingly advanced weighed water footprint impact index is that such an index hides all information related to impacts instead of making the impacts explicit. Some people have suggested that weighing has been successful in other fields, like the weighing of different greenhouse gasses by looking at their so-called 'global warming potential'. Suffice here to say that the cases are simply not similar, which makes copying the idea of weighing a thoughtless thing to do.

10. How does water footprint accounting relate to life cycle assessment?

The water footprint can be an indicator in the life cycle assessment (LCA) of a product. Being applied in an LCA is one of the many applications of the water footprint. In a global context, the water footprint is a relevant indicator of the how much of the globe's scarce freshwater resources are used for a certain product. In a more local context, the spatiotemporally explicit water footprint can be overlaid with a water-stress map in order to arrive at a spatiotemporally explicit water footprint impact map. The various impacts should subsequently be weighed and aggregated in order to arrive at an aggregated water footprint impact index. For LCA, an important question is how impacts can be aggregated – which is a specific requirement for LCA and not relevant to other applications of the water footprint. Other applications of the water footprint are for example identifying hotspot areas of the water footprints of certain products, consumer groups or businesses, and formulating response strategies to reduce water footprints and mitigate associated impacts. For these purposes, aggregation is not functional, because specification in type of water and space-time is essential in those applications.

114

11. How does the water footprint relate to ecological and carbon footprint?

The water-footprint concept is part of a larger family of concepts that have been developed in the environmental sciences over the past decade. A "footprint" in general has become known as a quantitative measure showing the appropriation of natural resources or pressure on the environment by human beings. The ecological footprint is a measure of the use of bio-productive space (hectares). The carbon footprint measures the amount of greenhouse gases produced, measured carbon dioxide equivalents (in tonnes). The water footprint measures water use (in cubic metres per year). The three indicators are complementary, since they measure completely different things. Methodologically there are many similarities between the different footprints, but each has its own peculiarities related to the uniqueness of the substance considered. Most typical for the water footprint is the importance of specifying space and time. This is necessary because the availability of water highly varies in space and time, so that water appropriation should always be considered in its local context.

12. What is the difference between water footprint and virtual water?

The water footprint is a term that refers to the water used to make a product. In this context we can also speak about the 'virtual water content' of a product instead of its 'water footprint'. The water footprint concept, however, has a wider application. We can for example speak about the water footprint of a consumer by looking at the water footprints of the goods and services consumed or about the water footprint of a producer (business, manufacturer, service provider) by looking at the water footprint of the goods and services produced by the producer. Furthermore, the water footprint concept does not simply refer to a water volume only, like in the case of the term 'virtual water content' of a product. The water footprint is a multidimensional indicator, not only referring to a water volume used, but also making explicit where the water footprint is located, what source of water is used, and when the water is used. The additional information is crucial in order to assess the local impacts of the water footprint of a product.

List of symbols

Symbol	Unit [a]	Explanation
α	-	leaching fraction, i.e. fraction of applied chemicals reaching freshwater bodies
AR	mass/area	application rate of a fertiliser or pesticide
c_{effl}	mass/volume	concentration of a chemical in an effluent
c_{max}	mass/volume	maximum acceptable concentration of a chemical in a receiving water body
c_{nat}	mass/volume	natural concentration of a chemical in the receiving water body
C	mass/time [b]	consumption of a product
CWR	length/time	crop water requirement
CWU_{blue}	volume/surface	blue crop water use
CWU_{green}	volume/surface	green crop water use
ΔT_{effl}	temperature	difference between temperature of effluent and receiving water body
ΔT_{max}	temperature	maximum acceptable temperature increase for a receiving water body
E	money/time	total economic value of a product produced in a business unit
$Effl$	volume/time	volume of effluent (wastewater flow)
EFR	volume/time	environmental flow requirement
ET_a	length/time	adjusted crop evapotranspiration (under actual conditions)
ET_{blue}	length/time	blue water evapotranspiration
ET_c	length/time	crop evapotranspiration (under optimal conditions)
ET_{env}	volume/time	evapotranspiration from land reserved for natural vegetation
ET_{green}	length/time	green water evapotranspiration
ET_o	length/time	reference crop evapotranspiration
ET_{unprod}	volume/time	evapotranspiration from land that cannot be made productive in crop production
$f_p[p,i]$	-	product fraction of output product p that is produced from input product i
$f_v[p]$	-	value fraction of output product p
IR	length/time	irrigation requirement
K_c	-	crop coefficient
K_{cb}	-	basal crop coefficient
K_e	-	soil evaporation coefficient
K_s	-	water stress coefficient
L	mass/time	load of a pollutant
L_{crit}	mass/time	critical load of a pollutant
P	mass/time [b]	production quantity of a product
P_{eff}	length/time	effective rainfall
$price$	money/mass	price of a product
R	volume/time	runoff from a catchment

Symbol	Unit [a]	Explanation
S_n	volume/time	national water saving through trade in a product
S_g	volume/time	global water saving through trade in a product
T	mass/time [b]	volume of trade in a product
T_e	mass/time [b]	volume of export of a product
T_i	mass/time [b]	volume of import of a product
T_{effl}	temperature	temperature of an effluent
T_{max}	temperature	maximum acceptable temperature for a receiving water body
T_{nat}	temperature	natural temperature of a receiving water body
V_b	volume/time	virtual-water budget of a delineated area (e.g. a nation)
V_e	volume/time	gross virtual-water export from a delineated area (e.g. a nation)
$V_{e,d}$	volume/time	gross virtual-water export insofar concerning export of domestically produced products
$V_{e,r}$	volume/time	gross virtual-water export insofar concerning re-export of imported products
V_i	volume/time	gross virtual-water import into a delineated area (e.g. a nation)
$V_{i,net}$	volume/time	net virtual-water import into a delineated area (e.g. a nation)
$w[i]$	mass	quantity of input product i
$w[p]$	mass	quantity of output product p
WA_{blue}	volume/time	blue water availability
WA_{green}	volume/time	green water availability
WD	%	national virtual-water import dependency
WF_{area}	volume/time	water footprint within a geographically delineated area
$WF_{area,nat}$	volume/time	water footprint within a nation
WF_{bus}	volume/time	water footprint of a business
$WF_{bus,oper}$	volume/time	operational water footprint of a business
$WF_{bus,sup}$	volume/time	supply-chain water footprint of a business
WF_{cons}	volume/time	water footprint of a consumer
$WF_{cons,dir}$	volume/time	direct water footprint of a consumer
$WF_{cons,indir}$	volume/time	indirect water footprint of a consumer
$WF_{cons,nat}$	volume/time	water footprint of national consumption
$WF_{cons,nat,dir}$	volume/time	direct water footprint of the consumers in a nation
$WF_{cons,nat,indir}$	volume/time	indirect water footprint of the consumers in a nation
$WF_{cons,nat,int}$	volume/time	internal water footprint of the consumers in a nation
$WF_{cons,nat,ext}$	volume/time	external water footprint of the consumers in a nation
WF_{proc}	volume/time [c]	water footprint of a process
$WF_{proc,blue}$	volume/time	blue water footprint of a process
$WF_{proc,green}$	volume/time	green water footprint of a process

Symbol	Unit [a]	Explanation
$WF_{proc,grey}$	volume/time	grey water footprint of a process
WF_{prod}	volume/mass [b]	water footprint of a product
WF^{*}_{prod}	volume/mass [b]	average water footprint of a product as available to the consumer or for export
$WFII_{blue}$	-	blue water footprint impact index
$WFII_{grey}$	-	grey water footprint impact index
WPL	-	water pollution level
WS_{blue}	-	blue water scarcity
WS_{green}	-	green water scarcity
WSS	%	national water self-sufficiency
Y	mass/surface	crop yield

Dimension	Explanation
i	input product
n	nation
n_e	exporting nation
n_i	importing nation
p	(output) product
q	process
s	process step
t	time
u	business unit
x	origin

[a] The unit of each variable is expressed here in general terms (mass, length, surface, volume, time). In water footprint accounting practice, mass is usually expressed in kg or ton, volume in litres or m^3 and time in day, month or year. Variables like rainfall, evapotranspiration and crop water requirement are usually expressed as mm per day, month or year. Yield and crop water use are usually expressed as ton/ha and m^3/ha respectively. Water quantities are usually expressed as a volume, under the assumption that 1 litre of water is equal to 1 kg. Working with this assumption, mass balances translate in volume balances. Obviously, in reporting numbers it is essential to specify the units used.

[b] A product water footprint is often expressed in terms of water volume per unit of mass; in this case we need to express production, consumption and trade in products in terms of mass/time. A product water footprint, however, can also be expressed in terms of water volume per unit of money; in this case we need to express production, consumption and trade in products in terms of monetary units/time. Other alternative ways to express a product water footprint are for example water volume / piece (for products that are counted per piece rather than weight), water volume / kcal (for food products) or water volume / joule (for electricity or fuels).

[c] A process water footprint is generally expressed in terms of water volume per unit of time. However, through dividing by the amount of product that results from the process (product units/time), a process water footprint also be expressed in terms of water volume per product unit.

Glossary

Ambient water quality standards – The maximum allowable amount of a substance in rivers, lakes or groundwater, given as a concentration. Ambient water quality standards can also refer to other properties of the water, such as temperature or pH. Standards are set to protect against anticipated adverse effects on human health or welfare, wildlife or the functioning of ecosystems.

Blue water – Fresh surface and groundwater, i.e. the water in freshwater lakes, rivers and aquifers.

Blue water availability – Runoff (through groundwater and rivers) minus environmental flow requirements. Blue water availability typically varies within the year and from year to year as well.

Blue water footprint – Volume of surface and groundwater consumed as a result of the production of a good or service. 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 ground- or surface water that does not return to the catchment from which it was withdrawn.

Blue water footprint impact index – An aggregated and weighed measure of the environmental impact of a blue water footprint at catchment level. It is based on two inputs: (1) the blue water footprint of a product, consumer or producer specified by catchment and by month, (2) the blue water scarcity by catchment and by month. The index is obtained by multiplying the two matrices and then summing the elements of the resultant matrix. The outcome can be interpreted as a blue water footprint weighed according to the blue water scarcity in the places and periods where the various blue water footprint components occur.

Blue water scarcity – The ratio of blue water footprint to blue water availability. Blue water scarcity varies within the year and from year to year.

Business water footprint – See 'water footprint of a business'.

Corporate water footprint – See 'water footprint of a business'.

Critical load – The load of pollutants that will fully consume the assimilation capacity of the receiving water body.

Crop water requirement – The total water needed for evapotranspiration, from planting to harvest for a given crop in a specific climate regime, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield.

Crop yield – Weight of harvested crop per unit of harvested area.

Direct water footprint – 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 to the water use by the consumer or producer. It is distinct from the indirect water footprint, which refers to the water consumption and pollution that can be associated with the production of the goods and services consumed by the consumer or the inputs used by the producer.

Economic water productivity – Economic value of the products produced per unit of water consumption or pollution. See also 'water productivity'.

Effective precipitation – The portion of the total precipitation that is retained by the soil so that it is available for crop production.

End-use water footprint of a product – When consumers use a product, there can be a water footprint in the end-use stage. Think about the water pollution that results from the use of soaps in the household. In this case one can speak about the end-use water footprint of a product. This footprint is strictly spoken not part of the product water footprint, but part of the consumer's water footprint.

Environmental flow requirements – The quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.

Evapotranspiration – Evaporation from the soil and soil surface where crops are grown, including the transpiration of water that actually passes crops.

External water footprint of national consumption – The part of the water footprint of national consumption that falls outside the nation considered. It refers to the appropriation of water resources in other nations for the production of goods and services that are imported into and consumed within the nation considered.

Global water saving through trade - International trade can save freshwater globally if a water-intensive commodity is traded from an area where it is produced with high water productivity (small water footprint) to an area with lower water productivity (large water footprint).

Green water – The precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Green water can be made productive for crop growth (but not all green water can be taken up by crops, because there will always be evaporation from the soil and because not all periods of the year or areas are suitable for crop growth).

Green water availability – The evapotranspiration of rainwater from land minus evapotranspiration from land reserved for natural vegetation and minus evapotranspiration from land that cannot be made productive.

Green water footprint – Volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (products based on crops or wood), where it refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood.

Green water footprint impact index – An aggregated and weighed measure of the environmental impact of a green water footprint at catchment level. It is based on two inputs: (1) the green water footprint of a product, consumer or producer specified by catchment and by month, (2) the green water scarcity by catchment and by month. The index is obtained by multiplying the two matrices and then summing the elements of the resultant matrix. The outcome can be interpreted as a green water footprint weighed according to the green water scarcity in the places and periods where the various green water footprint components occur.

Green water scarcity – The ratio of green water footprint to green water availability. Green water scarcity varies within the year and from year to year.

Grey water footprint – The grey water footprint of a product is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on 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 agreed water quality standards.

Grey water footprint impact index – An aggregated and weighed measure of the environmental impact of a grey water footprint at catchment level. It is based on two inputs: (1) the grey water footprint of a product, consumer or producer specified by catchment and by month, (2) the water pollution level by catchment and by month. The index is obtained by multiplying the two matrices and then summing the elements of the resultant matrix. The outcome can be interpreted as a grey water footprint weighed according to the water pollution level in the places and periods where the various grey water footprint components occur.

Hotspot identification – The process of identifying 'water footprint hotspots' in space and time based on two criteria: (1) the water footprint of a product, consumer or producer is significant in this area and period of the year, and (2) problems of water scarcity and pollution occur in this area in this period of the year. The hotspots are associated with particular components in the total water footprint of the product, consumer or producer. Hotspots deserve most attention when formulating response measures.

Indirect water footprint – The indirect water footprint of a consumer or producer refers to the freshwater consumption and pollution 'behind' products being consumed or produced. It 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.

Internal water footprint of national consumption – The part of the water footprint of national consumption that falls inside the nation, i.e. the appropriation of domestic water resources for producing goods and services that are consumed domestically.

Irrigation requirement - The quantity of water exclusive of precipitation, i.e. quantity of irrigation water, required for normal crop production. It includes soil evaporation and some unavoidable losses under the given conditions. It is usually expressed in water-depth units (millimetres) and may be stated in monthly, seasonal or annual terms, or for a crop period.

National water footprint – Is the same as what is more accurately called the 'water footprint of national consumption', which is defined as the total amount of fresh water that is used to produce the goods and services consumed by the inhabitants of the nation. Part of this water footprint lies outside the territory of the nation. The term should not be confused with the 'water footprint within a nation', which refers to the total freshwater volume consumed or polluted within the territory of the nation.

National water saving through trade - A nation can preserve its domestic freshwater resources by importing a water-intensive product instead of producing it domestically.

Operational water footprint of a business – The operational (or direct) water footprint of a business is the volume of freshwater consumed or polluted due to its own operations.

Organisational water footprint – See 'water footprint of a business'.

Overhead water footprint – The water footprint of a product consists of two elements: the use of freshwater that can immediately be related to the product and the use of freshwater in overhead activities. The latter element is called the 'overhead water footprint'. The overhead water footprint refers to freshwater use that in first instance cannot be fully associated with the production of the specific product considered, but

refers to freshwater use that associates with supporting activities and materials used in the business, which produces not just this specific product but other products as well. The overhead water footprint of a business has to be distributed over the various business products, which is done based on the relative value per product. The overhead water footprint includes for example the freshwater use in the toilets and kitchen of a factory and the freshwater use behind the concrete and steel used in the factory and machineries.

Production system – A production system of a product consists of all the sequential process steps applied to produce the product. A production system can be a linear chain of processes, it can take the shape of a product tree (many inputs ultimately resulting in one output product) or it may rather look like a complex network of interlinked processes that eventually lead one or more products.

Product tree – See 'production system'.

Return flow – The part of the water withdrawn for an agricultural, industrial or domestic purpose that returns to the ground- or surface water in the same catchment as where it was abstracted. This water can potentially be withdrawn and used again.

Supply-chain water footprint of a business – The supply-chain (or indirect) water footprint of a business is the volume of freshwater consumed or polluted to produce all the goods and services that form the input of production of a business.

Virtual-water balance – The virtual-water balance of a geographically delineated area (e.g. a nation or catchment area) over a certain time period is defined as the net import of virtual water over this period, which is equal to the gross import of virtual water minus the gross export. A positive virtual-water balance implies net inflow of virtual water to the nation from other nations. A negative balance means net outflow of virtual water.

Virtual-water content – The virtual-water content of a product is the freshwater "embodied" in the product, not in real sense, but in virtual sense. It refers to the volume of water consumed or polluted for producing the product, measured over its full production chain. If a nation exports/imports such a product, it exports/imports water in virtual form. The 'virtual-water content of a product' is the same as 'the water footprint of a product', but the former refers to the water volume embodied in the product alone, while the latter term refers to that volume, but also to which sort of water is being used and to when and where that water is being used. The water footprint of a product is thus a multi-dimensional indicator, whereas virtual-water content refers to a volume alone.

Virtual-water export – The virtual-water export from a geographically delineated area (e.g. a nation or catchment area) is the volume of virtual water associated with the export of goods or services from the area. It is the total volume of freshwater consumed or polluted to produce the products for export.

Virtual-water flow – The virtual-water flow between two geographically delineated areas (e.g. two nations) is the volume of virtual water that is being transferred from the one to the another area as a result of product trade.

Virtual-water import – The virtual-water import into a geographically delineated area (e.g. a nation or catchment area) is the volume of virtual water associated with the import of goods or services into the area. It is the total volume of freshwater used (in the export areas) to produce the products. Viewed from

the perspective of the importing area, this water can be seen as an additional source of water that comes on top of the available water resources within the area itself.

Water abstraction – See 'water withdrawal'.

Water consumption – 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.

Water footprint – The water footprint is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business. Water use is measured in terms of water volumes consumed (evaporated) and/or polluted per unit of time. A water footprint can be calculated for a particular product, for any well-defined group of consumers (e.g. an individual, family, village, city, province, state or nation) or producers (e.g. a public organization, private enterprise or economic sector). The water footprint is a geographically explicit indicator, not only showing volumes of water use and pollution, but also the locations.

Water footprint accounting – The step in water footprint assessment that refers to collecting factual, empirical data on water footprints with a scope and depth as defined earlier.

Water footprint assessment – Quantifying a water footprint, assessing its impacts and formulating a response. The assessment includes four phases: setting goals and scope; water footprint accounting; water footprint sustainability assessment; and water footprint response formulation.

Water footprint impact indices – See 'blue–', 'green–' and 'grey water footprint impact index'.

Water footprint of a business – The water footprint of a business – which can also be called alternatively corporate or organizational water footprint – is defined as the total volume of freshwater that is used directly and indirectly to run and support a business. The water footprint of a business consists of two components: the direct water use by the producer (for producing/manufacturing or for supporting activities) and the indirect water use (the water use in the producer's supply chain). The 'water footprint of a business' is the same as the total 'water footprint of the business output products'.

Water footprint of a consumer – Is defined as the total volume of freshwater consumed and polluted for the production of the goods and services consumed by the consumer. It is calculated by adding the direct water use by people and their indirect water use. The latter can be found by multiplying all goods and services consumed by their respective water footprint.

Water footprint of national consumption – Is defined as the total amount of fresh water that is used to produce the goods and services consumed by the inhabitants of the nation. The water footprint of national consumption can be assessed in two ways. The bottom-up approach is to consider the sum of all products consumed multiplied with their respective product water footprint. In the top-down approach, the water footprint of national consumption is calculated as the total use of domestic water resources plus the gross virtual-water import minus the gross virtual-water export.

Water footprint of national production – Another term for the 'water footprint within a nation'.

Water footprint of a product – The water footprint of a product (a commodity, good or service) is the total volume of freshwater used to produce the product, summed over the various steps of the production chain. The water footprint of a product refers not only to the total volume of water used; it also refers to where and when the water is used.

Water footprint sustainability assessment – Assessing the sustainability of a water footprint from an environmental, social and economic perspective, at local, river basin as well as global level.

Water footprint within a geographically delineated area – Is defined as the total freshwater consumption and pollution within the boundaries of the area. The area can be for example a hydrological unit like a catchment area or a river basin or an administrative unit like a municipality, province, state or nation.

Water footprint within a nation – Is defined as the total freshwater volume consumed or polluted within the territory of the nation.

Water neutral – A process, product, consumer, community or business is water neutral when (1) its water footprint has been avoided and reduced where possible, particularly in places with a high degree of water scarcity or pollution, and (2) when the negative environmental, social and economic externalities of the remaining water footprint have been offset (compensated). In some particular cases, when interference with the water cycle can be completely avoided – e.g. by full water recycling and zero waste – 'water neutral' means that the water footprint is nullified; in other cases, like in the case of crop growth, the water footprint cannot be nullified. Therefore 'water neutral' does not necessarily mean that the water footprint is brought down to zero, but that it is reduced as much as possible and that the negative economic, social and environmental externalities of the remaining water footprint are fully compensated.

Water offsetting – Offsetting the negative impacts of a water footprint is part of water neutrality. Offsetting is a last step, after a prior effort of avoiding and reducing a water footprint and its impacts. Compensation can be done by contributing to (e.g. by investing in) a more sustainable and equitable use of water in the hydrological units in which the impacts of the remaining water footprint are located.

Water pollution level – Degree of pollution of the runoff flow, measured as the fraction of the pollution assimilation capacity of runoff actually consumed. A water pollution level of hundred percent means that the pollution assimilation capacity of the runoff flow has been fully consumed.

Water productivity – Product units produced per unit of water consumption or pollution. Water productivity (product units/m^3) is the inverse of the water footprint (m^3/product unit). Blue water productivity refers to the product units obtained per m^3 of blue water consumed. Green water productivity refers to the product units obtained per m^3 of green water consumed. Grey water productivity refers to the product units obtained per m^3 of grey water produced. The term 'water productivity' is a similar term as the terms labour productivity or land productivity, but now production is divided over the water input. When water productivity is measured in monetary output instead of physical output per unit of water, one can speak about 'economic water productivity'.

Water scarcity – See 'blue water scarcity' and 'green water scarcity'.

Water self-sufficiency vs. water dependency of a nation - The 'water self-sufficiency' of a nation is defined as the ratio of the internal to the total water footprint of national consumption. It denotes the degree to which the nation supplies the water needed for the production of the domestic demand for goods and

services. Self-sufficiency is 100% if all the water needed is available and indeed taken from within the own territory. Water self-sufficiency approaches zero if the demand for goods and services in a nation is largely met with virtual-water imports. Nations with import of virtual water depend, de facto, on the water resources available in other parts of the world. The 'virtual-water import dependency' of a nation is defined as the ratio of the external to the total water footprint of national consumption.

Water withdrawal – The volume of freshwater abstraction from surface or groundwater. Part of the freshwater withdrawal will evaporate, another part will return to the catchment where it was withdrawn and yet another part may return to another catchment or the sea.

THE INTEREST IN THE WATER FOOTPRINT IS ROOTED IN THE RECOGNITION THAT HUMAN IMPACTS ON FRESHWATER SYSTEMS CAN ULTIMATELY BE LINKED TO HUMAN CONSUMPTION, AND THAT ISSUES LIKE WATER SHORTAGES AND POLLUTION CAN BE BETTER UNDERSTOOD AND ADDRESSED BY CONSIDERING PRODUCTION AND SUPPLY CHAINS AS A WHOLE. WATER PROBLEMS ARE OFTEN CLOSELY TIED TO THE STRUCTURE OF THE GLOBAL ECONOMY. MANY COUNTRIES HAVE SIGNIFICANTLY EXTERNALISED THEIR WATER FOOTPRINT, IMPORTING WATER-INTENSIVE GOODS FROM ELSEWHERE. THIS PUTS PRESSURE ON THE WATER RESOURCES IN THE EXPORTING REGIONS, WHERE TOO OFTEN MECHANISMS FOR WISE WATER GOVERNANCE AND CONSERVATION ARE LACKING. NOT ONLY GOVERNMENTS, BUT ALSO CONSUMERS, BUSINESSES AND CIVIL SOCIETY COMMUNITIES CAN PLAY A ROLE IN ACHIEVING A BETTER MANAGEMENT OF WATER RESOURCES.

Water Footprint Network

Enschede, The Netherlands

Phone: +31 53 489 4320

Fax: +31 53 489 5377

E-mail: info@waterfootprint.org

www.waterfootprint.org

Water Footprint