Box 3.1 *The relation between the different sorts of water footprints*

- 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 (for example, a municipality, province, state, nation, catchment or river basin) = the sum of the process water footprints of all processes taking place in the area.

water footprint of national consumption is equal to the water footprint within the nation insofar as it is 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 the exporting 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.

3.3 Water footprint of a process step

3.3.1 Blue water footprint

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

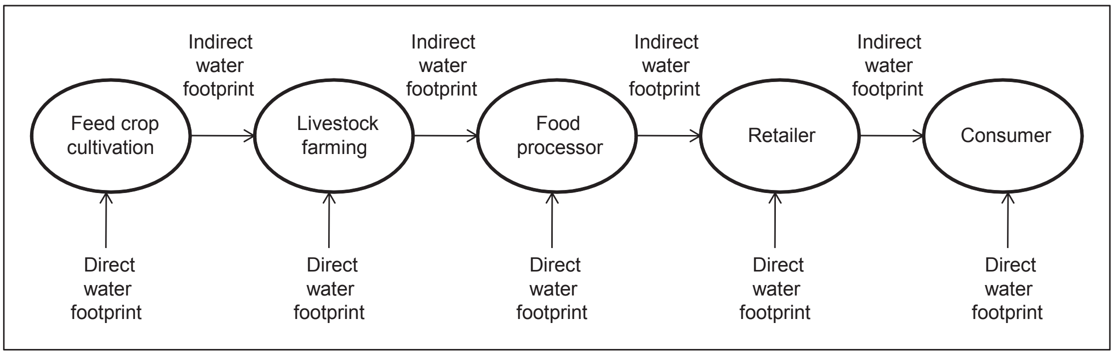

Figure 3.3 The direct and indirect water footprint in each stage of the supply chain of an animal product

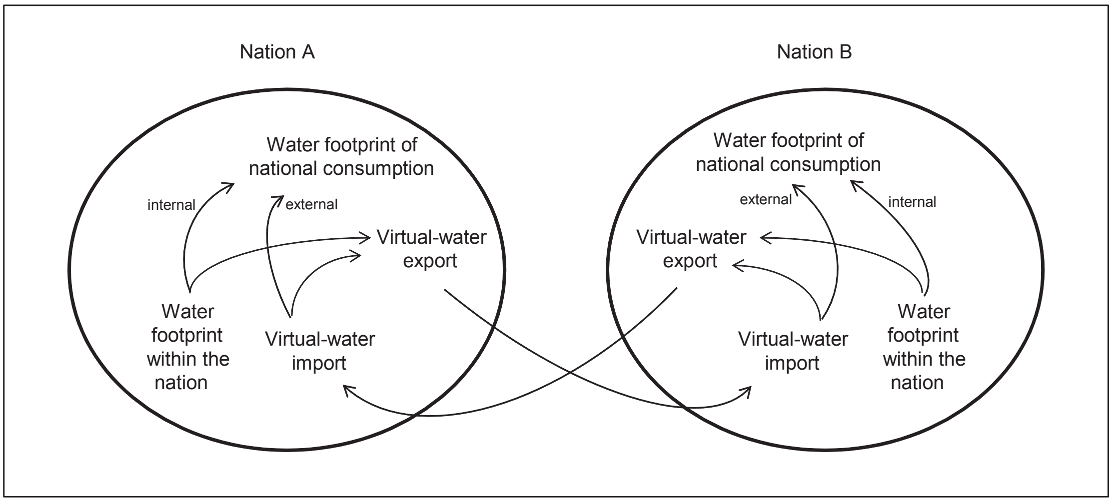

Figure 3.4 The relation between the water footprint of national consumption and the water footprint within a nation in a simplified example for two trading nations

1. Water evaporates;
2. Water is incorporated into the product;
3. Water does not return to the same catchment area, for example, it is returned to another catchment area or the sea;
4. Water does not return in the same period, for example, 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. All production-related evaporation counts, including the water that evaporates during water storage (for example, from artificial water reservoirs), transport (for example,

Box 3.2 *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.

from open canals), processing (for example, evaporation of heated water that is not recollected) and collection and disposal (for example, from drainage canals and from wastewater treatment plants).

'Consumptive water use' does not mean that the water disappears, because water will remain within the cycle and always return 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 (in other words, 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 groundwater and surface water flows not consumed for human purposes, is left to sustain the ecosystems that depend on the groundwater and surface water flows.

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

$$WF_{proc,blue} = BlueWaterEvaporation + BlueWaterIncorporation + LostReturnflow \quad [\text{volume/time}] \qquad (1)$$

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.

In assessing the blue water footprint of a process it may be relevant (depending on the scope of the study) 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 insufficient data, which is the reason the distinction is often not made. It is possible, however, if data allow, to specify the blue water footprint by source (see examples in Aldaya and Llamas, 2008; Aldaya and Hoekstra, 2010; Mekonnen and Hoekstra, 2010b).

When specifying the total blue water footprint by source, one may also like to explicitly distinguish the consumptive use of harvested rainwater. Rainwater harvesting is a bit of a particular case, since one may argue whether harvested rainwater is green or blue water. Mostly, rainwater harvesting refers to the collection of rain that otherwise would become run-off. Since consumptive use of harvested rainwater will subtract from run-off, we recommend to consider such water use as a blue water footprint. Various sorts of rainwater harvesting techniques exist to provide drinking water, water for livestock or water for irrigating crops or gardens. As long as one speaks of local collection of run-off – as in the case of rainwater harvesting from rooftops or other hard surfaces or in the case of leading the rain to small ponds – one can categorize consumptive use of this water under the blue water footprint. If, on the contrary, one speaks of measures to increase the soil water holding capacity or about green rooftops to retain rainwater, consumptive use of this water for crop production will fall under the green water footprint.

The unit of the blue process water footprint is water volume per unit of time, for example, 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. In Box 3.3 we reflect on where to obtain the data necessary for blue water footprint accounting.

Box 3.3 *Data sources for the calculation of a blue water footprint*

Industrial processes: Each component of the blue process water footprint can be measured, directly or indirectly. It is generally known how much water is added in order to become part of the product. How much water evaporates during storage, transport, processing and disposal is generally not measured directly, but can be inferred from the difference between abstraction and final disposal volumes. Ideally, one can rely on databases that contain typical data on consumptive water use for various types of manufacturing processes. Such databases, however, do hardly exist and generally contain data on water withdrawals (abstractions), not on consumptive water use. Besides, these databases generally lack the necessary details and contain data on water use per industrial sector (for example, sugar refineries, textile mills, paper mills and so on) rather than per manufacturing process. Two data-rich compendiums are Gleick (1993) and Van der Leeden et al (1990), but both are US-focused and mainly limited to data on water withdrawals. One can also consult proprietary databases such as Ecoinvent (2010) but such databases generally provide data on water withdrawals, not consumptive water use. The best sources for blue water consumption in manufacturing processes are the manufacturers themselves or regional or global branch organizations.

Agricultural processes: Available statistics on blue water use in agriculture generally show total water withdrawals for irrigation only, not blue *consumptive* water use. Measuring water evapotranspiration from a field is a laborious task. And even when total evapotranspiration was measured, one would need to estimate which part of the total is blue water. Therefore one will generally rely on water balance models that use data on climate, soil, crop characteristics and actual irrigation as input. Section 3.3.4 shows in more detail how one can estimate the blue water footprint in crop growth based on a water balance model. Based on global maps on where different crops are grown and on global maps of climate, soils and irrigation, a few research groups in the world have started to make spatial-explicit estimates of blue (and green) water footprints of crop growing. For wheat alone, for example, four global datasets are available: Liu et al (2007, 2009), Siebert and Döll (2010), Mekonnen and Hoekstra (2010a) and Zwart et al (2010). At the website of the Water Footprint Network – www.waterfootprint.org – geographically explicit data on the water footprint of crop growing are available for all major crops in the world. These datasets can be used for water footprint accounting at Level B (see Table 2.1). For accounting at Level C, one will have to apply an appropriate water balance model oneself, together with locally specific input data.

We finalize this section by considering two specific cases for which it may not be immediately clear to the reader how to properly account. The first case concerns the issue of water recycling and reuse. The second case concerns the question of how to account in the case of an inter-basin water transfer.

Water recycling and reuse

Water recycling and reuse are often used as two interchangeable terms. Here we define 'water recycling' specifically as the *on-site* reuse of water *for the same purpose* and 'water reuse' as the reuse of water elsewhere, possibly for another purpose. In the case of recycling, we can make an additional distinction between recycling of wastewater (by treating it for reuse) and recycling of evaporated water (by condensing water vapour for reuse). The different sorts of water recycling and reuse are shown for a simple example in Figure 3.5. The figure shows two processes, the second of which reuses (treated) wastewater from the first. The scheme shows that for the blue water footprints of both processes it is the consumptive water use (evaporation and incorporation into products) that counts. Water recycling and reuse can be instrumental in reducing the blue water footprint of a process only when it effectively reduces consumptive water use. Water recycling and reuse may also be instrumental in reducing the grey water footprint of water users, but this will be discussed in Section 3.3.3.

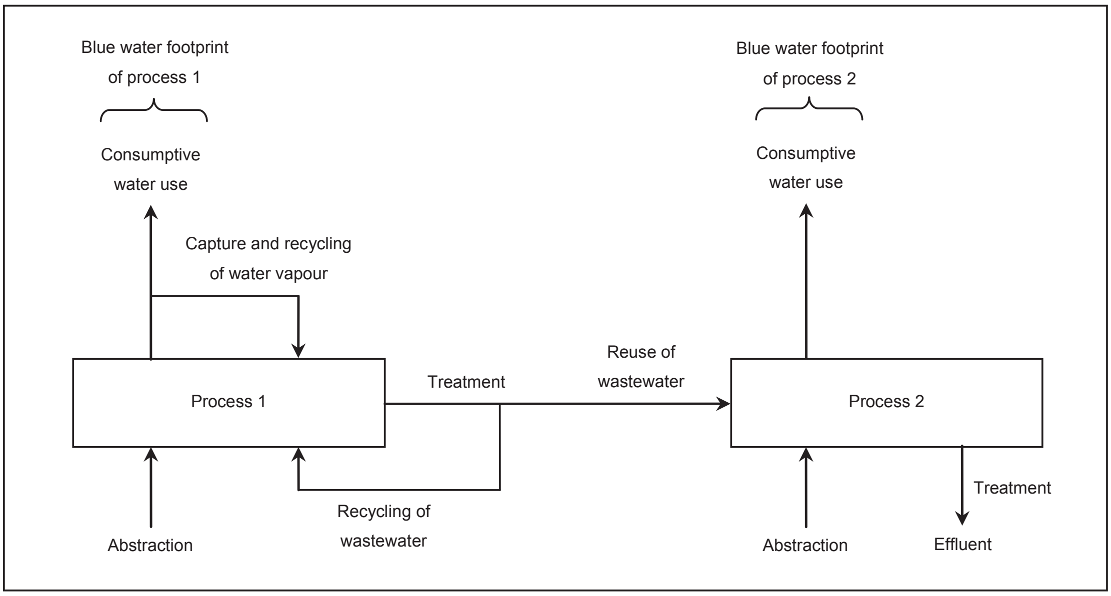

Figure 3.5 Blue water footprint accounting in the case of water recycling and reuse

Inter-basin water transfer

An inter-basin water transfer is the abstraction of water from a river basin A and move it – through pipelines, canals or bulk transport (for example, by lorry or ship) – to another river basin B. According to the blue water footprint definition, moving water away from a river basin is a blue water footprint within that basin, because it is 'consumptive water use'. The blue water footprint of the total transfer will be allocated to the beneficiaries of the water in the receiving river basin. Thus, processes in basin B that use water from another basin A have a blue water footprint located in basin A, the size of which is equal to the amount of water they receive plus the possible losses on the way. If the water users in the receiving river basin B return (part of) the used water to their own basin, we see that water is 'added' to the water resources in river basin B. This 'added' water may compensate for the blue water footprint of other users that have consumed water from basin B; in that sense one may argue that the inter-basin water transfer creates a 'negative blue water footprint' in the receiving river basin (insofar as the water does not evaporate and indeed adds to the water system of the receiving basin). The negative blue water footprint in basin B partly compensates the positive blue water footprint of other users in basin B. Note that it does not compensate for the blue water footprint in river basin A! When the goal is to assess the overall water footprint of humans in basin B, we recommend to include a possible 'negative blue water footprint' that exists as a result of real water transfer into the basin (provided that it indeed compensates for a positive blue water footprint in the basin in the same period). In the case of water footprint accounts for individual processes, products, consumers or producers, one should leave calculated negative blue water footprints out of the footprint accounts in order to make a clear separation between the discussion about the gross water footprint of a process, product, consumer or producer and the discussion about possible compensation. The issue of compensation (subtractability) is debatable and should be dealt with separately from the accounting phase. It has been argued that doing good in one basin (for example, through a negative blue water footprint in that basin) cannot compensate for the positive blue water footprint in another basin, since water depletion and resulting impacts in one place will not be solved by adding water somewhere else. In this case, adding a calculated negative blue water footprint to the calculated positive blue water footprint would result in a misleading figure. Read more on the impossibility to compensate a water footprint in one basin by adding water in another basin in Chapter 5 (Box 5.2).

3.3.2 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:

$$WF_{proc,green} = GreenWaterEvaporation + GreenWaterIncorporation \quad [\text{volume/time}] \qquad (2)$$

The distinction between the blue and green water footprint is important because the hydrological, environmental and social impacts, as well as 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 with a crop model suitable for estimating evapotranspiration based on input data on climate, soil and crop characteristics. In Section 3.3.4 we will present in more detail how one can estimate the green water footprint in crop growth.

3.3.3 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 natural background concentrations and existing ambient water quality standards. The grey water footprint concept has grown out of the recognition that the size of water pollution can be expressed in terms of the volume of water that is required to dilute pollutants such that they become harmless (Box 3.4).

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).

Box 3.4 *The history of the grey water footprint concept*

The grey water footprint refers to the volume of water that is required to assimilate waste, quantified as the volume of water needed to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards. The idea of expressing water pollution in terms of a water volume needed to dilute the waste is not new. Falkenmark and Lindh (1974) proposed as a rule of thumb to reckon with a dilution factor of 10–50 times the wastewater flow. Postel et al (1996) applied a dilution factor for waste absorption of 28 litres per second per 1000 population. These generic dilution factors do not account for the sort of pollution and the level of treatment before disposal, but implicitly assume some average characteristics of human waste flows. Chapagain et al (2006b) proposed to make the dilution factor dependent on the type of pollutant and to use the ambient water quality standard for a certain pollutant as the criterion to quantify the dilution requirement. The term 'grey water footprint' was for the first time introduced by Hoekstra and Chapagain (2008) and defined as the pollutant load divided by the maximum acceptable concentration in the receiving water body. A bit later, it was recognized that the grey water footprint is better calculated as the pollutant load divided by the difference between the maximum acceptable and the natural background concentration (Hoekstra et al, 2009a). The work of the Water Footprint Network's grey water footprint working group (Zarate, 2010a) has further resulted in a number of refinements, including the recognition that the quality of intake water should be taken into account and the idea of a multi-tier approach in order to distinguish between different levels of detail in assessing a grey water footprint in the case of diffuse pollution.

Although the grey water footprint can be understood as a 'dilution water requirement', we prefer not to use that term since it appeared to cause confusion with some people who thought that the term implies 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. Treatment of wastewater before disposal will obviously result in a reduced grey water footprint, possibly down to zero.

Some recent studies that include quantification of grey water footprints include: Dabrowski et al (2009); Ercin et al (2009); Gerbens-Leenes and Hoekstra (2009); Van Oel et al (2009); Aldaya and Hoekstra (2010); Bulsink et al (2010); Chapagain and Hoekstra (2010); and Mekonnen and Hoekstra (2010a, b).

$$WF_{proc,grey} = \frac{L}{c_{max} - c_{nat}} \quad \text{[volume/time]} \qquad (3)$$

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

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.

Grey water footprint calculations are carried out using ambient water quality standards for the receiving freshwater body, in other words, 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 example, 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 one grey water footprint in one place and another grey water footprint in another place. This is reasonable, because the required water volume for assimilating a certain pollutant 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 and natural concentrations have been used in preparing a grey water footprint account.

Both ambient water quality standards and natural background concentrations vary for surface and groundwater bodies. Thresholds in groundwater are often based on requirements for drinking water, while maximum acceptable concentrations in surface waters are typically determined by ecological considerations. One could therefore propose to calculate the grey water footprint separately for surface and groundwater systems. The problem with doing so, however, is that groundwater generally ends up as surface water, so that for a pollutant load to groundwater one can better take the difference between water quality standard and natural background concentration for the most critical water body (either the groundwater system or the surface water system). For loads to the surface water system one can take the relevant data as for the surface water system. When it is precisely known which loads arrive (first) in the groundwater system and which loads in the surface water system, it makes sense to show two components of the grey water footprint: the grey groundwater footprint and the grey surface-water footprint.

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. As long as the calculated grey water footprint is smaller than the existing river flow or groundwater flow, 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. 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 approach taken in grey water footprint accounting is the same as the so-called critical-load approach (Box 3.5). In both cases, the basic recognition is that the room for waste uptake of a water body is limited by the difference between the maximum and the natural concentration. The critical load refers to the situation where the room for waste uptake has been fully consumed. At the critical load, the grey water footprint will be equal to the available water flow, which is then required in full to dilute the chemicals down to acceptable concentrations.

Box 3.5 *The concept of critical load*

When the load into a flowing water body reaches a certain 'critical load', the grey water footprint will be equal to the run-off, which means that full run-off is appropriated for waste assimilation. 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 run-off of the water body (R, in volume/time) by the difference between the maximum acceptable and natural concentration:

$$L_{crit} = R \times (c_{max} - c_{nat}) \quad \text{[mass/time]}$$

The concept of the 'critical load' is similar as the 'total maximum daily load' (TMDL) developed by the US Environmental Protection Agency (EPA, 2010a). The TMDL calculates the maximum amount of a pollutant allowed to enter a water body so that the water body will meet and continue to meet water quality standards for that particular pollutant and allocates that load to point and diffuse sources, which include both anthropogenic and natural background sources of the pollutant. Another concept closely related to the concept of 'critical load' is the concept of 'maximum permissible addition' (MPA), which is defined as the 'maximum permissible concentration' (MPC) minus the background concentration and thus equivalent to $c_{max} - c_{nat}$ (Crommentuijn et al, 2000).

Point sources of water pollution

In the case of point sources of water pollution, in other words, when chemicals are directly released into a surface water body in the form of a wastewater disposal, the load can be estimated by measuring the effluent volume and the concentration of a chemical in the effluent. More precisely: the pollutant load can be calculated as the effluent volume (*Effl*, in volume/time) multiplied by the concentration of the pollutant in the effluent (c_{effl}, in mass/volume) minus the water volume of the abstraction (*Abstr*, in volume/time) multiplied by the actual concentration of the intake water (c_{act}, in mass/volume). The grey water footprint can then be calculated as follows:

$$WF_{proc,grey} = \frac{L}{c_{max} - c_{nat}} = \frac{Effl \times c_{effl} - Abstr \times c_{act}}{c_{max} - c_{nat}} \quad \text{[volume/time]} \qquad (4)$$

The pollutant load L is thus defined as the load that comes on top of the load that was already contained in the receiving water body before interference by the activity considered. An example of the application of this equation in a concrete case is given in Appendix IV. Under most circumstances, the amount of chemicals discharged into a water body ($Effl \times c_{effl}$) will be equal or larger than the amount abstracted chemicals ($Abstr \times c_{act}$), so the load is positive. In exceptional circumstances (either because $c_{effl} < c_{act}$ or because $Effl < Abstr$), one could calculate a negative load, which has to be neglected for water footprint accounts (so one should account for a zero water footprint in such a case). The positive contribution made to the environment in the exceptional case of a 'negative load' is to be appreciated but should not be counted in the water footprint accounts, in order to separate the discussion of possible water footprint compensation from existing positive water footprints. Water footprint compensation or 'offsetting' is a debate in itself (see Box 5.2 in Chapter 5), which should be held and made explicit, not hidden in the accounts. It is further to be noted that, when water for a certain process is abstracted in catchment A while the effluent is discharged into catchment B, one should take $Abstr = 0$ for the calculation of the grey water footprint in catchment B.

When there is no consumptive water use, in other words, when the effluent volume equals the abstraction volume, above equation simplifies into:

$$WF_{proc,grey} = \frac{c_{effl} - c_{act}}{c_{max} - c_{nat}} \times Effl \qquad \text{[volume/time]} \qquad (5)$$

The factor that stands in front of *Effl* is the so-called 'dilution factor', which represents the number of times that the effluent volume has to be diluted with ambient water in order to arrive at the maximum acceptable concentration level. How this equation works out under a number of particular cases is discussed in Box 3.6.

Water recycling and reuse

From Equation 5, one can see that water recycling or water reuse will affect the grey water footprint. When – after treatment when necessary – water is fully recycled or reused for the same or another purpose, there is no effluent to the environment, so the grey water footprint will be zero. If after one time or a number of times of reuse, however, the water is still disposed into the environment, there will be a grey water footprint, related to the quality of the effluent of course.

Wastewater treatment

When wastewater is treated before it is disposed into the environment, this obviously lowers the concentration of pollutants in the final effluent, so it will lower the grey water footprint. It should be noted that the grey water footprint of a process depends on the quality of the effluent as it is finally disposed into the environment, not on the quality before treatment. Wastewater treatment

Box 3.6 *The grey water footprint in different cases of point-source pollution*

Let us consider the common case in which the effluent volume is equal (or close) to the abstraction volume.

- When $c_{effl} = c_{act}$ 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 a certain fraction of the effluent volume. When, in addition, $c_{act} = c_{nat}$ then the grey water footprint is precisely 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 run-off.
- When $c_{effl} < c_{act}$ the calculated grey water footprint would be negative, which is explained by the fact that the effluent is cleaner than the intake water. 'Cleaning' when the river is actually still under natural conditions does not make much sense, because some background concentration is apparently natural. 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 this positively contributes to water quality. However, calculated negative grey water footprints have to be ignored from the accounts, in order to separate the discussion on somebody's actual positive water footprint from the discussion on someone's possible role in terms of compensation. The issue of compensation or 'offsetting' of water footprints is discussed in Chapter 5 (Box 5.2).
- When $c_{max} = 0$ (the case of a complete ban of a highly persistent or toxic pollutant, for which also $c_{nat} = 0$), 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 $c_{max} = c_{nat}$ creates 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.

can bring the grey water footprint down to zero when the concentrations of pollutants in the effluent are equal to or lower than the concentrations in the water as it was abstracted. As a side remark, it is noted here that the process of wastewater treatment in itself will have a blue water footprint when evaporation takes place during the treatment process in open basins.

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 (°C) divided by the maximum acceptable temperature increase (°C) times the effluent volume (volume/time):

$$WF_{proc,grey} = \frac{T_{effl} - T_{act}}{T_{\max} - T_{nat}} \times Effl \qquad \text{[volume/time]} \tag{6}$$

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

Diffuse sources of water pollution

Estimating the chemical load in the case of diffuse sources of water pollution is not as straightforward as in the case of point sources. When a chemical is applied on or put into the soil, as in the case of solid waste disposal or use of fertilizers 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 (put on or into the soil) that reaches the groundwater or surface water. The amount of chemicals applied can be measured, but the fraction of applied chemicals that reaches the groundwater or surface water cannot be measured, since it enters the water in a diffuse way, so it is not clear where and when to measure. As a solution, one can measure the water quality at the outlet of a catchment, but different sources of pollution come together, so that the challenge becomes to apportion the measured concentrations to different sources. Therefore, it is common practice, and also recommended here, to estimate the fraction of applied chemicals that enter the water system by using simple or more advanced models. The simplest model is to assume that a certain fixed fraction of the applied chemicals finally reach the ground- or surface water:

$$WF_{proc,grey} = \frac{L}{c_{max} - c_{nat}} = \frac{\alpha \times Appl}{c_{max} - c_{nat}} \qquad \text{[volume/time]} \tag{7}$$

The dimensionless factor α stands for the leaching-run-off fraction, defined as the fraction of applied chemicals reaching freshwater bodies. The variable *Appl*

Box 3.7 *Three-tier approach in estimating diffuse pollution loads*

A three-tier approach is recommended for estimating diffuse pollution loads, similar to the one of the Intergovernmental Panel on Climate Change (IPCC) for estimating greenhouse gas emissions (IPCC, 2006). From Tier 1 to 3, the accuracy increases but the feasibility decreases.

- Tier 1 uses a fixed fraction to translate data on the amount of chemicals applied to the soil to an estimate of the amount of chemicals that enter the groundwater or surface water system. The fraction is to be derived from existing literature and may depend on the chemical considered. This Tier 1 estimate will suffice as a first rough estimate but obviously excludes relevant factors such as soil type, agricultural practice, soil hydrology and interaction between different chemicals in the soil.
- Tier 2 applies standardized and simplified model approaches, which can be used based on widely available data (such as agricultural nutrient balances, soil loss data, basic hydrologic, petrologic and hydromorphologic information). These simple and standardized model approaches should be derived from widely accepted and validated models.
- Tier 3 uses sophisticated modelling techniques given that the available resources allow it and the chosen topic requires it. Whereas detailed mechanistic models of contaminant flows through soil are available, their complexity often renders them inappropriate for use in Tier 3 type modelling of the diffuse pollution load. However, validated empirical models driven by information on farm practices, and which use simplified soil and weather data are presently available for use in diffuse-load studies. Tier 3 studies should be used to further refine Tier 2 approaches.

represents the application of chemicals on or into the soil in a certain process (in mass/time). This model is the simplest, least detailed method to estimate the grey water footprint in the case of diffuse pollution; so it is recommended only as the default method, to be used if time does not allow a more detailed study. Higher levels of detail are possible; it is proposed to distinguish three levels of detail: from Tier 1 (the default method) to Tier 3 (the most detailed method). In Tiers 2 and 3, more specific data and advanced methods are to be used (Box 3.7).

The effect of evaporation on water quality

A specific form of 'pollution' can occur when water quality deteriorates as a result of evaporation. When a part of a water flow evaporates, the concentrations of chemicals in the remaining water flow will increase (because when water evaporates the chemicals in the water stay behind). Consider, as an example, the case of high salt concentrations in drainage water from irrigated fields. When there is continued irrigation with little drainage compared to the volume of water evaporating, the salts naturally contained in the irrigation water accumulate in the soil (since the water evaporates, not the salt). As a result, also the drainage water will have a relatively high salt content. One may call this 'pollution'. But obviously it is another sort of pollution than when humans add chemicals to the water, because in this case there is no addition of chemicals by humans, but the naturally present chemicals get concentrated by water evaporation. We can generalize this case to all cases where 'water is taken out of the system through evaporation'. It also happens, for instance, in artificial reservoirs where water evaporates and chemicals accumulate.

Increasing the chemical concentration in a water body by 'taking water out through evaporation while leaving the chemicals in' is effectively the same as adding a certain additional load. If one takes out X m^3 of pure water, the 'equivalent load' is X m^3 times the natural concentration in the water body (c_{nat} in mass per m^3). The 'equivalent load' of $X \times c_{nat}$ (expressed as a mass) is natural, but no longer embedded in natural water, because the water was taken away (it evaporated). This 'equivalent load' has to be assimilated by other natural water. The grey water footprint related to this 'equivalent load' can be calculated with the standard equation, whereby the grey water footprint is equal to the 'equivalent load' divided by the difference between the maximum and natural concentration (Equation 3). This grey water footprint will come on top of grey water footprints in the catchment related to real loads (in other words, chemical loads added by human activities).

Integration over time and different pollutants

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, that is 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.

As a final note, it is observed here that grey water footprints are measured based on the (human-induced) loads that *enter into* freshwater bodies, not on the basis of the loads that can finally be measured in the river or groundwater flow at some *downstream* point. Since water quality evolves over time and in the course of the water flow as a result of natural processes, the load of a certain chemical at a downstream point can be distinctly different from the sum of the loads that once entered the stream (upstream). The choice to measure the grey water footprint at the point where pollutants enter the groundwater or surface water system has the advantage that it is relatively simple – because one does not need to model the processes that change water quality along the river – and safe – because water quality may improve along the flow of a river by decay processes – but it is unclear why one should take improved water quality downstream as an indicator instead of measuring the immediate impact of a load at the point where it enters the system. While the grey water footprint indicator thus does not account for natural processes that may improve water quality along the water flow, it does also not account for processes that consider the combined effect of pollutants, which may sometimes be greater than what one may expect on the basis of the concentrations of chemicals when considered separately. In the end, the grey water footprint strongly depends on ambient water quality standards (maximum acceptable concentrations), which is reasonable given the fact that such standards are set based on the best available knowledge about the possible harmful effects of chemicals including their possible interaction with other chemicals.

3.3.4 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 and so on. Wood from trees and shrubs is used for timber, paper and fuel. 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:

$$WF_{proc} = WF_{proc,green} + WF_{proc,blue} + WF_{proc,grey} \qquad \text{[volume/mass]} \qquad (8)$$

We will express all process water footprints in this section per unit of product, namely 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:

$$WF_{proc,green} = \frac{CWU_{green}}{Y} \quad \text{[volume/mass]} \tag{9}$$

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y} \quad \text{[volume/mass]} \tag{10}$$

Yields for annual crops can be taken as given in yield statistics. In the case of perennial crops, one should consider the average annual yield over the full lifespan of the crop. In this way, one accounts 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. Also for the crop water use, one needs to take the average annual crop water use over the life span of the 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 to the field per hectare (AR, kg/ha) times the leaching-run-off fraction (α) divided by the maximum acceptable concentration (c_{max}, kg/m^3) minus the natural concentration for the pollutant considered (c_{nat}, kg/m^3) and then divided by the crop yield (Y, ton/ha).

$$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{\max} - c_{nat})}{Y} \quad \text{[volume/mass]} \tag{11}$$

The pollutants generally consist of fertilizers (nitrogen, phosphorus and so on), pesticides and insecticides. One has to consider only the 'waste flow' to freshwater bodies, which is generally a fraction of the total application of fertilizers or pesticides to the field. One needs to account for only the most critical pollutant, that is the pollutant 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:

$$CWU_{green} = 10 \times \sum_{d=1}^{\mathrm{lgp}} ET_{green} \quad \text{[volume/area]} \tag{12}$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{\mathrm{lgp}} ET_{blue} \quad \text{[volume/area]} \tag{13}$$

in which ET_{green} represents green water evapotranspiration and ET_{blue} blue water evapotranspiration. The factor 10 is meant to convert water depths in millimetres 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 lifespan of a permanent crop or tree, one should look at the annual average of evapotranspiration over the full lifespan of the crop or tree. Suppose, for example, that a certain perennial crop has a lifespan of 20 years, while it gives a yield only from the sixth year on. In this case, the crop water use over the 20 years needs to be divided over the total yield over the 15 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, 2010b), which is based on the method described in Allen et al (1998). Yet another model is the AQUACROP model, specifically developed for estimating crop growth and *ET* under water-deficit conditions (FAO, 2010e).

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 (as the underlying model includes a dynamic soil water balance). A comprehensive manual for the practical use of the CROPWAT program is available online (FAO, 2010b). Appendix I summarizes how to use the 'crop water requirement option' to estimate green and blue water evapotranspiration under optimal conditions; it also summarizes 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 II.

Estimating the green, blue and grey water footprints of growing a crop requires a large number of data sources (Box 3.8). 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 per cent of the wet mass, for vegetables often 90–95 per cent. 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 per cent of the evaporated water, up to 1 per cent at most.

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 3.6). 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.

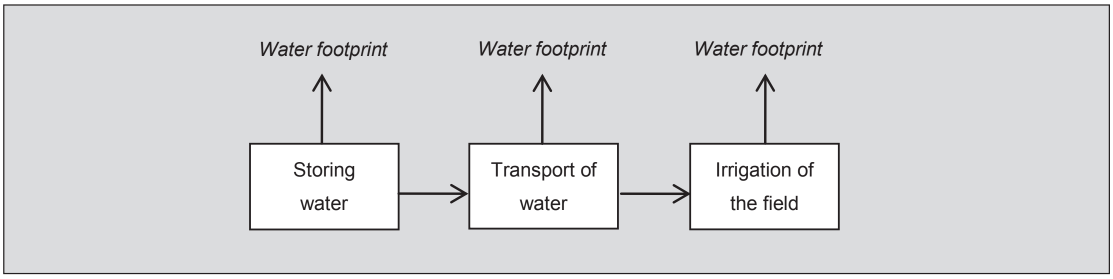

Figure 3.6 The subsequent processes in irrigation: storing water, transport of water, irrigation on the field. Each process step has its own water footprint

Box 3.8 *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, 2010a) 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, 2010g).
- **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 (2010b), 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, 2010f).
- **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).
- **Crop yields**: Yield data can best be obtained locally, at the spatial resolution level required. One has to make sure that it is clear how yields are measured (for example, what part of the crop, dry or wet weight). A global database is available through the FAO (2010d).
- **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, 2010h). 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, 2010). These data also provide rain-fed crop growing areas for the same 26 crops.
- **Fertilizer application rates**: Preferably one uses local data. A useful global database is FertiStat (FAO, 2010c). The International Fertilizer Association (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. The National Agricultural Statistics Service (NASS, 2009) provides an online database for the US with chemical use per crop. CropLife Foundation (2006) provides a database on pesticides use in the USA. Eurostat (2007) gives data for Europe.
- **Leaching-run-off fraction**: No databases available. One will have to work with experimental data from field studies and make rough assumptions. One can assume 10 per cent for nitrogen fertilizers, following Chapagain et al (2006b).
- **Ambient water quality standards**: Preferably use local standards as regulated in legislation. This information is available for some parts of the world, such as for the European Union (EU, 2008), the US (EPA, 2010b), Canada (Canadian Council of Ministers of the Environment, 2010), Australia/New Zealand (ANZECC and ARMCANZ, 2000), China (Chinese Ministry of Environmental Protection, 2002), Japan (Japanese Ministry of the Environment, 2010), Austria (Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2010), Brazil (CONAMA, 2005), South Africa (South African Department of Water Affairs and Forestry, 1996), Germany (LAWA-AO, 2007) and the UK (UKTAG, 2008). A compilation can be found in MacDonald et al (2000). 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 example, EU (2000) and EPA (2005).
- **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 US see, for example, Clark et al (2000) and Smith et al (2003); for Austria see Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (2010); for Germany see LAWA-AO (2007). 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.
- **Actual concentration of the intake water:** A global database on actual concentrations is available through UNEP (2009).

Appendix II

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, 2010b). 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, 2010b).

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 II.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 II.1). In the temperate north of Spain, beets are planted in the spring and harvested in the autumn. In warmer southern areas (Andalusia), sugar beets 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 the UN's Food and Agriculture Organization (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, 2010b). Besides, in the irrigation schedule option, soil data are required to estimate the soil water balance. Soil information was also obtained from FAO (2010b).

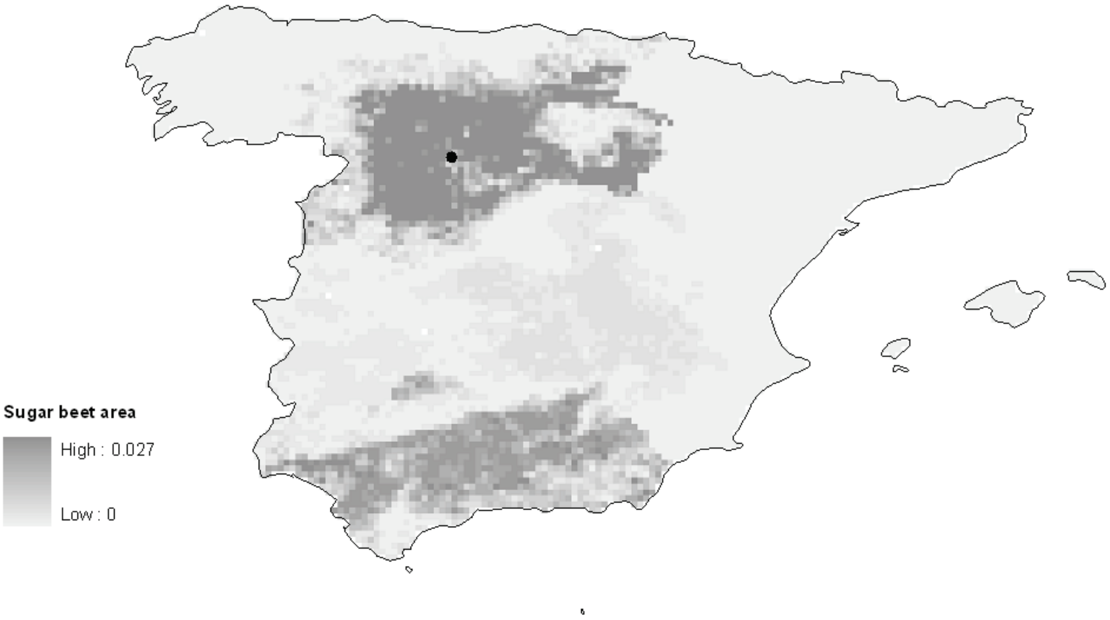

Figure II.1 Climate station in Valladolid (Spain) (dot in black) and sugar beet harvested area in Spain (unit: proportion of grid cell area)

Source of sugar beet area: Monfreda et al (2008)

Table II.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

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 method of the Soil Conservation Service of the United States Department of Agriculture (USDA SCS) was chosen as it is one of the most widely used methods. The model calculates ET_c as follows:

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

Month	*Period*	*Stage*	K_c –	ET_c mm/day	ET_c mm/period	P_{eff} mm/period	*Irr. req.* mm/period	ET_{green} mm/period	ET_{blue} 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

$$ET_c = K_c \times ET_o \quad \text{[length/time]} \tag{62}$$

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 II.2).

$$ET_{green} = \min\,(ET_c, P_{eff}) \quad \text{[length/time]} \tag{63}$$

$$ET_{blue} = \max\,(0, ET_c - P_{eff}) \quad \text{[length/time]} \tag{64}$$

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):

$$ET_a = K_s \times ET_c = K_s \times K_c \times ET_o \quad \text{[length/time]} \tag{65}$$

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}) in rain-fed agriculture, the 'no irrigation (rain-fed)' choice is selected within the 'options' button on the Toolbar (Table II.3). Under this scenario, the green water evapotranspired (ET_{green}) is equal to the total evapotranspiration as simulated, which is given under 'actual water use by crop' as specified in the model output. The blue water evapotranspired (ET_{blue}) is obviously zero in this case.

To estimate the green and blue water evapotranspiration in irrigated agriculture, 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 while 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 10mm or less per wetting event are applied. In the case of surface or sprinkler irrigation, irrigation depths are 40mm or more. In the sugar beet production in Valladolid, 40mm are applied every seven days (Table II.4). After running the model with the selected irrigation options, the total water evapotranspired is equal to ET_a over the growing period as given in the model output ('actual water use by crop'). After running the

Table II.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 mm	K_s –	ET_a mm	Depl %	Net Irr mm	Deficit mm	Loss mm	Gr. Irr mm	Flow 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 II.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 40mm
Field eff. 70%

Table format: Daily soil moisture balance

Date	Day	Stage	Rain mm	K_s –	ET_a mm	Depl %	Net Irr mm	Deficit mm	Loss mm	Gr. Irr mm	Flow 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		%

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

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:

$$WF_{proc,green} = \frac{CWU_{green}}{Y} \quad \text{[volume/mass]} \tag{66}$$

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y} \quad \text{[volume/mass]} \tag{67}$$

The outcome of both options is given in Table II.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.

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 per cent, which means that the water footprint of sugar beet is 0.75–0.80m³/ton if we look at incorporated water alone. This is less than 1 per cent of the water footprint related to evaporated water.

Table II.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_a	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	125	668	793	1250	6680	7930	81	15	82	98

* Source: MARM (2009) period 2000–2006

Table II.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 leaching or running off to water bodies 10%*	*max. conc.*	*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, 2010c)
** Source: MARM (2009) period 2000–2006

Grey component in the process water footprint

The grey component in the process water footprint of a primary crop (m^3/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 II.6). The quantity of nitrogen that reaches free flowing water bodies has been assumed to be 10 per cent 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 nitrogen is calculated considering the volume of nitrogen that leaches or runs off (ton/ton) and the maximum allowable concentration in the free flowing surface water bodies. As ambient water quality standard for nitrogen, we have used 10mg/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, 2010c).