CHAPTER

The water footprint of industry

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INTRODUCTION

The World Economic Forum has listed water scarcity as one of the three global systemic risks of highest concern in an assessment based on a broad global survey of risk perception among representatives from business, academia, civil society, governments, and international organizations (WEF, 2014). Freshwater scarcity manifests itself in the form of declining groundwater tables, reduced river flows, shrinking lakes, and heavily polluted waters, and also in increasing costs of supply and treatment, intermittent supplies, and conflicts over water (Hoekstra, 2014a). Future water scarcity will grow as a result of various drivers such as population and economic growth, increased demands for animal products and biofuels, and climate change (Ercin and Hoekstra, 2014). The private sector is becoming aware of the problem of freshwater scarcity but is facing the challenge of formulating effective responses. Even companies operating in water-abundant regions can be vulnerable to water scarcity, because the supply chains of most companies stretch across the globe. An estimated 22% of global water consumption and pollution relates to the production of export commodities (Hoekstra and Mekonnen, 2012). Countries such as the United States, Brazil, Argentina, Australia, India, and the People's Republic of China are significant virtual water exporters, meaning that they intensively use domestic water resources for producing export commodities. In contrast, countries in Europe, North Africa, and the Middle East as well as Mexico and Japan are dominated by virtual water import, meaning that they rely on import goods produced with water resources elsewhere. The water use behind those imported goods is often not sustainable, because many of the export regions overexploit their resources.

Increasingly, companies start exploring their water footprint (WF) by looking at both their operations and supply chain. Key questions that industry leaders pose themselves are: where is my WF located?; what risks does water scarcity impose to my business?; how sustainable is the WF in the catchments where my operations and supply chain processes are located?; where and how can water use efficiency be increased?; and what is good water stewardship? The demand for

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new types of data emerges, types of data that were usually not collected. The focus shifts from relatively simple questions regarding whether the company has sufficient water abstraction permits and whether wastewater disposal standards are met to the more pressing question regarding how the company actually contributes to the overexploitation and pollution of water resources, not only through its own facilities but also through its supply chain. Sustainability is not implied by having permits and meeting standards. Most experience with collecting the new types of data required and with addressing questions about good water stewardship is within the food and beverage sector, which most clearly depends on water. In other industries, the connection with water is not always clear, because the connection is indirect and mostly through the supply chain. The aim of this chapter is to review experiences with WF accounting in different sectors of the economy and to reflect on the question of what good water stewardship is.

First, I discuss what new perspective the WF concept brings to the table compared with the traditional way of looking at water use. Second, I discuss and compare three methods to trace resource use and pollution over supply chains: environmental footprint assessment (EFA), life cycle assessment (LCA), and environmentally extended input−output analysis (EE-IOA). Third, I review some of the recent literature on direct and indirect WFs of different sectors of the economy. Finally, I discuss the emerging concept of water stewardship for business and the challenge of creating greater product and business transparency.

THE WF CONCEPT

The WF is a measure of freshwater appropriation underlying a certain product or consumption pattern. Three components are distinguished: the blue, green, and gray WF (Hoekstra et al., 2011). The blue WF measures the volume of water abstracted from the ground or surface water system minus the volume of water returned to the system. It thus refers to the sum of the water flow that evaporates during the process of production, the water incorporated into a product, and the water released in another catchment. The blue WF differs from the conventional way of measuring freshwater use by looking at net rather than gross water withdrawal. This is done because it makes more sense to look at net water withdrawal if one is interested in the effect of water use on water scarcity within a catchment. Return flows can be reused within the catchment, unlike the water flow that evaporates or is captured within a product. The green WF refers to the volume of rainwater consumed in a production process. This is particularly relevant in agriculture and forestry, where it refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood. The gray WF is an indicator of freshwater pollution and defined as the volume of freshwater that is required to assimilate a load of pollutants based on natural background concentrations and existing ambient water quality standards. The advantage of expressing water pollution in terms of the water volume required for assimilating the pollutants, rather than in terms of concentrations of contaminants, is that this brings water pollution into the same unit as consumptive use. In this way, the use of water as a drain and the use of water as a resource, two competing uses, become comparable. The WF thus refers to both consumptive water use [of rainwater (the green WF) and of surface and groundwater (the blue WF)] and degenerative or degradative water use (the gray WF).

As a measure of freshwater use, the WF differs from the classical measure of "water withdrawal" in several ways. The term "water withdrawal," also called "water abstraction" or often simply "water use", refers to the extraction of water from the groundwater or a surface water body like a river, lake, or artificial storage reservoir. It thus refers to what we call *blue* water use. The WF is not restricted to measuring blue water use; it also measures the use of green water resources (the green WF) and the volume of pollution (the gray WF). Another difference between the WF and the classical way of measuring water use was mentioned previously: the classical measure of "water use" always refers to gross blue water abstraction, whereas the blue WF refers to net blue water abstraction. Another difference between the classical way of measuring water use and the WF is that the latter concept can be used to measure water use over supply chains. When we talk about the WF of a product, we refer to the water consumption and pollution in all stages of the supply chain of the product. When we speak about the WF of a producer or a consumer, we refer to the full WF of all the products produced or consumed.

Thus, the WF offers a wider perspective on how a product, producer, or consumer relates to the use of freshwater systems. It is a volumetric measure of water consumption and pollution. WF accounts give spatiotemporally explicit information on how water is appropriated for various human purposes. 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 who make use of the same system. The WF within a catchment needs to be compared with the maximum sustainable WF in the catchment to understand the sustainability of water use. The WF of a specific process or product needs to be compared with a WF benchmark based on the best available technology and practice to understand the efficiency of water use. The WF per capita for a community can be compared with the WF of other communities to understand the degree of equitable sharing of limited water resources. WF accounts can thus feed the discussion about the sustainability, efficiency, and equitability of water use and allocation (Hoekstra, 2013, 2014b).

The definition of the green and blue WF can best be understood by considering the water balance of a river basin (Figure 7.1). The total annual water availability in a catchment area is given by the annual volume of precipitation, which will leave the basin partly through evapotranspiration and partly through runoff to the sea. Both the evaporative flow and the runoff can be appropriated by humans. The green WF refers to the human use of the evaporative flow from the land

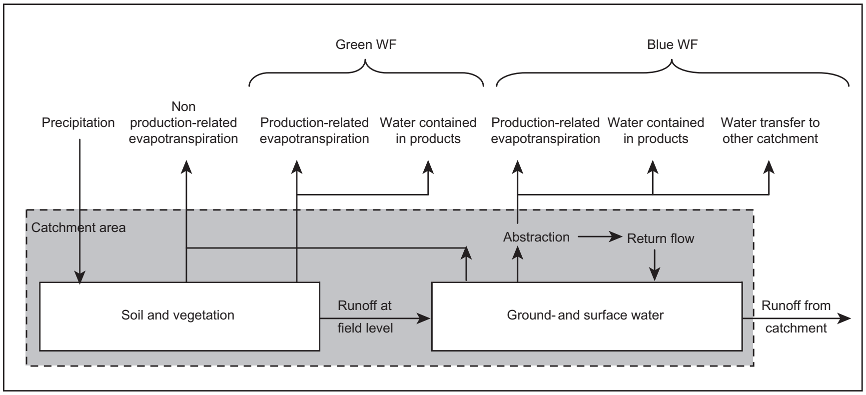

FIGURE 7.1

Definition of the green and blue WF in relation to the water balance of a catchment area.

From Hoekstra et al. (2011) with permission from the publishers.

surface, mostly for growing crops or production forest. The blue WF refers to the consumptive use of the runoff flow, i.e., the net abstraction of runoff from the catchment. The term "water consumption" can be confusing, because many people, particularly those not aware of the big difference between gross and net water abstraction, use the term for gross water abstraction. Specialists, though, define water consumption as net blue water abstraction (gross abstraction minus return flow). Evaporation is generally considered as a loss to the catchment. Even though evaporated water will always return in the form of precipitation on a global scale, this will not alleviate the water scarcity in the catchment during the period that the river is emptied because of net water abstractions. Moisture recycling on smaller spatial scales is generally only modest.

The definition of the gray WF is clarified in Figure 7.2. The basis for the calculation is the anthropogenic load of a substance into a freshwater body (groundwater, river, lake), i.e., the additional load caused by a human activity (e.g., a production process). We should acknowledge that the effluent from an industry might contain certain amounts of chemicals that were already in the water abstracted. Therefore, we should look at the *additional* load to a freshwater body as a result of a certain activity. Furthermore, we should look at the load of a substance that really enters the river, lake, or groundwater, which means that if an effluent is treated before disposal, then we have to consider the load of chemicals in the effluent that remains *after* treatment. The critical load in a freshwater body is defined as the difference between the maximum acceptable and natural concentration of a chemical for the receiving water body multiplied by the renewal rate of the freshwater body. Note that for the maximum allowable concentration, we have to use the ambient water quality standard for the receiving freshwater body, not the effluent standard (Franke et al., 2013). In a river, the renewal rate is equal

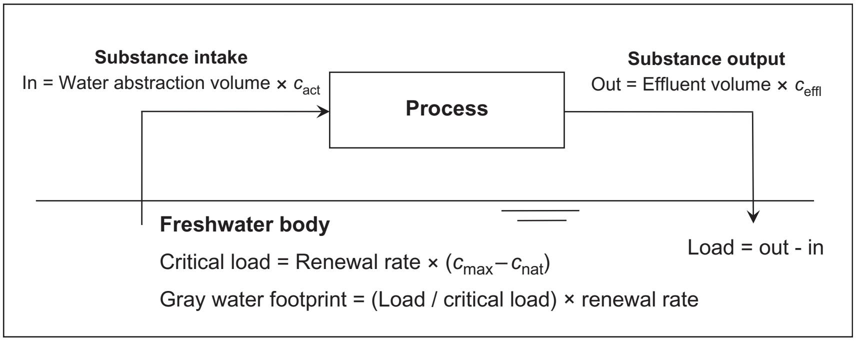

FIGURE 7.2

Definition of the gray WF based on the load of a chemical into a freshwater body. The symbols c_{act}, c_{nat}, and c_{max} refer to the actual, natural, and maximum allowable concentration of the chemical in the freshwater body; c_{effl} refers to the concentration of the chemical in the effluent.

to runoff; in a groundwater reservoir, the renewal rate is equal to groundwater recharge, which (over the longer-term) is the same as groundwater runoff. In a lake, the renewal rate equals the flow through the lake. The gray WF is calculated as the pollutant load to a freshwater body divided by the critical load multiplied by the renewal rate of that freshwater body. Defined in this way, it means that when the gray WF onto a freshwater body becomes as big as the renewal rate of this freshwater body, the assimilation capacity has been fully used. When the size of the gray WF in a catchment exceeds the size of runoff from this catchment, pollution is bigger than the assimilation capacity, resulting in a violation of the maximum acceptable concentration. When an effluent contains different types of pollutants, as is usually the case, the gray WF is determined by the pollutant that is most critical, i.e., the one that gives the largest pollutant-specific gray WF. Thermal pollution can be dealt with in a way similar to that of pollutants, whereby the load consists of heat and the assimilation capacity depends on the accepted temperature increase of the receiving water body (Hoekstra et al., 2011).

METHODS TO TRACE NATURAL RESOURCES USE AND POLLUTION OVER SUPPLY CHAINS

Different methods have been developed to analyze direct and indirect natural resources use and emissions in relation to products or economic sectors. They have all been applied specifically to trace direct and indirect water use and pollution over supply chains as well. I discuss the methods of EFA, LCA, and EE-IOA. Each of the three methods has its specific goal, approach, and focus, but there are commonalities across the methods as well. They all focus on understanding natural resource use and emissions along supply or value chains. EFA focuses on macro-questions about resource use sustainability, efficiency, equitability, and security. LCA concentrates on the comparative analysis of environmental impacts of products. EE-IOA focuses on understanding how natural resource use and environmental impacts can be traced throughout the economy.

The field of EFA comprises methods to quantify and map land, water, material, carbon, and other environmental footprints and to assess the sustainability of these footprints as well as the efficiency, equitability, and security of resource use (Hoekstra and Wiedmann, 2014). WF assessment (WFA) can be regarded as a specific branch of this field and refers to the full range of activities to quantify and locate the WF of a process, product, producer, or consumer or to quantify in space and time the WF in a specified geographic area; assess the environmental sustainability, economic efficiency, and social equitability of WFs; and formulate a response strategy (Hoekstra et al., 2011). Broadly speaking, the goal of assessing WFs is to analyze how human activities or specific products relate to issues of water scarcity and pollution, and to see how consumption, production, trade, and specific products can become more sustainable from a water perspective.

LCA is a method for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise (and others) (Rebitzer et al., 2004). The assessment includes all stages of the life cycle of a product from cradle-to-grave (from material extraction to returning of wastes to nature). An LCA study includes four phases: setting a goal and scope; inventory accounting; impact assessment; and interpretation. Water use and pollution can be considered specific impact categories within LCA (Kounina et al., 2013). LCA focuses on *comparing* the environmental impacts of alternative processes, materials, products, or designs.

EE-IOA is a method for studying the relation between different sectors of the economy and indirect natural resource use and environmental impacts. It combines the classical monetary input−output formalism with satellite accounts containing data on resource use and emissions into the environment. Over the past decade, we have seen quite a number of applications of EE-IOA to analyze “embodied” water flows through the economy (Daniels et al., 2011). Applications have been performed, e.g., for Australia (Lenzen and Foran, 2001), Spain (Duarte et al., 2002; Cazcarro et al., 2013), the United Kingdom (Yu et al., 2010; Feng et al., 2011b), the People’s Republic of China (Zhao et al., 2009; Zhang and Anadon, 2014), and the city of Beijing (Zhang et al., 2011). Input−output models basically show monetary flows between sectors within the economy; environmentally extended input−output models usually express water use in terms of liters per dollar (or other currency). Most environmentally extended input−output models also have some form of accounting of product flows in physical units, but because of the aggregation of specific economic activities into sectors it remains difficult to reach the same high level of detail as achieved in a process-based WFA or LCA. Both WFA and LCA enable an analysis of water use in all processes of the value chain and attribution of the water use along value chains to specific products. A promising path in this respect is the method of so-called *hybrid* environmentally extended input–output modeling, in which physical flows are integrated into the model (Ewing et al., 2012; Steen-Olsen et al., 2012).

Process-based WFA and LCA are generally constrained by the fact that parts of the value chain have to be omitted from the analysis for practical reasons. This problem does not occur in input–output modeling. Therefore, there is a development to enhance process-based WFA and LCA with the advantage of input–output modeling. In the case of LCA, this results in the so-called hybrid LCA approach (Finnveden et al., 2009). In hybrid LCA, the environmental impacts of flows that were not included in the process-based LCA are estimated with an environmentally extended input–output model. In the case of WFA, a similar development can be expected (Feng et al., 2011a).

The difference between EFA and LCA is the focus on sustainability of production and consumption at a macro-level of the former and the focus on comparing potential environmental impact at process and product level of the latter (Box 7.1). Typical questions in EFA studies relate to how different processes and products contribute to the overall footprints at larger scales, how different consumption patterns influence the overall footprint, whether footprints at the larger scales remain within their maximum sustainable levels, how footprints can be reduced by better technology, whether different people have equitable shares in the total footprint of humanity, and what externalization of footprints may imply for resource security (Hoekstra and Wiedmann, 2014). LCA is designed to compare the potential environmental impact of one product over its full value chain with the potential impact of another product, or to compare the differences in potential impact between different product designs or alternative production processes.

At the level of basic data, EFA and LCA require similar data. The data collection and analysis required in the accounting stage of a product-focused WFA (as opposed to a geographic-focused or consumption-focused WFA) is very similar to what is needed in the inventory stage of a water-focused LCA (Boulay et al., 2013).

EFA, LCA, and EE-IOA are not static analytical methods, but rather are young fields undergoing development. We can observe a development in the past few years in which a fruitful exchange between the three fields leads to the adoption of approaches from one field to the other. In EFA studies, we have seen the adoption of life cycle accounting procedures from LCA and the exploration of using input–output models to calculate national and sector footprints, in addition to the already existing bottom-up and top-down trade balance approaches. In LCA we recently observed, fed by experiences in EFA, an interest to develop methods to perform an LCA for a whole organization instead of for a product, and to perform LCAs for consumer lifestyles or for national consumption as a whole (Hellweg and Milà i Canals, 2014). Additionally, based on experiences in EE-IOA, the LCA community is exploring hybrid LCA methods, as already

BOX 7.1 THE SUSTAINABILITY OF CUTTING TREES—THE FUNDAMENTAL DIFFERENCE BETWEEN LCA AND EFA

Is it sustainable to cut a tree? Although a relevant question, it is impossible to answer this question in isolated form. It is difficult to argue that cutting just one tree is not sustainable. After a tree has been cut, a new one will grow, so it is sustainable. However, if one takes this insight on the sustainability of cutting one tree to conclude that one can cut all forests, one cannot maintain that this is sustainable. The reason why answering a simple question like this tree-cutting question causes a fundamental problem is that sustainability is a concept that cannot be applied at the level of single activities, but only at the level of a system as a whole. Still, there is a strong wish among people to measure the sustainability of single activities, because individuals undertake single activities and consume goods and services that relate to series of single activities to produce them. The methods of LCA and EFA deal with this problem in fundamentally different ways. In LCA, the approach is to leave the larger question of sustainability and look at *comparative* contributions of different activities to natural resource appropriation, emissions, and potential impacts on the larger scale. In other words, LCA addresses the question of how cutting one tree compares with cutting two trees, a question that is not difficult to answer. In EFA, the approach is to estimate humanity's total natural resource appropriation and emissions and to compare that with the Earth's carrying or assimilation capacity. Both methods struggle in a similar way with how to compare apples and pears, e.g., how to compare cutting trees with polluting water. The approach in LCA is to *weigh* different types of primary resource use or emissions according to their potential final impact on human health and ecosystem health. The approach in EFA is to compare the different types of resource use and pollution with their respective maximum sustainable levels. The great similarity between LCA and EFA is that resource use and emissions are analyzed per process (activity) and per product (by analyzing the processes along supply chains). The difference comes when LCA starts weighing different types of resource use and emissions based on their potential impact and comparing alternative processes or products according to their overall potential environmental impact. In contrast, EFA adds the resource use and emissions of different activities to get a complete picture, analyze the sustainability of the whole, and study the relative contribution of different processes, products, and consumers to the total. In many applications, though, the difference between LCA and EFA is not so clear. By comparing the footprints of two different processes or products, EFA also allows for comparative analysis. However, the comparative analysis is partial in this case, because different footprints are not weighted and added to get a measure of "overall potential environmental impact." One can also extend an LCA from comparing products to comparing consumption patterns, which is on the larger scale typically for EFA. The fundamental difference between LCA and EFA in the way they treat the tree-cutting question, however, remains.

mentioned. The EE-IOA practice improves in the direction of hybrid methods that include physical accounting and have greater granularity in the analysis, fed by the practices in the EFA and LCA fields. This mutual enrichment and, to some extent, convergence of approaches does not imply that the three methods will grow into one. They may develop into a more consistent framework of coherent methods, but the fact that different sorts of questions will remain implies that different approaches will continue to be necessary.

All three methods—EFA, LCA, and EE-IOA—have a focus on environmental issues, leaving out social issues (like labor conditions, human rights). Principally, there is nothing that necessarily restricts the methods to environmental issues.

Broadly speaking, one can trace all sorts of process characteristics along supply chains. The oldest forms of accounting along supply chains are the accounting of monetary added value and the accounting of material flows and energy use along supply chains. Material flow analysis (MFA) or substance flow analysis (SFA) aims at the quantification of stocks and flows of materials or substances in a well-defined system, drawing mass balances for each subsystem and the system as a whole. Energy flow analysis aims at quantifying the energy content of flows within an economy. The innovation of EFA, LCA, and EE-IOA lies in the attribution of resource use, emissions, or impacts along supply chains to products and final consumption. In this context, one speaks about the embodied, embedded, indirect or virtual land, water, and energy in a product or consumption pattern, or the indirect emissions. When doing so, the method of EE-IOA is linked to traditional economic accounting, which is a strong point of this method. The methods of EFA and LCA are linked to physical accounting, which is their strength. In all three fields, we observe efforts to enhance the methods and broaden the scope with an increasing number of hybrid approaches.

DIRECT AND INDIRECT WFs OF DIFFERENT SECTORS OF THE ECONOMY

THE IMPORTANCE OF WATER USE IN THE PRIMARY SECTOR

Usually, economic activities are categorized into three different sectors. The primary sector of the economy, the sector that extracts or harvests products from the Earth, has the largest WF on Earth. This sector includes activities like agriculture, forestry, fishing, aquaculture, mining, and quarrying. The green WF of humanity is nearly entirely concentrated within the primary sector. It has been estimated that approximately 92% of the blue WF of humanity is just in agriculture alone (Table 7.1).

The secondary sector covers the manufacturing of goods in the economy, including the processing of materials produced by the primary sector. It also includes construction and the public utility industries of electricity, gas, and water. Sometimes, the public utility industries are also mentioned under the tertiary (service) sector, because they not only produce something (electricity, gas, purified water) but also supply it to customers (as a service). Water utilities could even partly fall under the primary sector, because part of the activity is the abstraction of water from the environment (rivers, lakes, and groundwater). The work of water utilities comprises water collection, purification, distribution and supply, wastewater collection (sewerage), wastewater treatment, materials recovery, and wastewater disposal. It is rather common to categorize the whole water utility sector under the secondary sector. The tertiary sector is the service industry and covers services to both businesses and final consumers. This sector includes activities like retail and wholesale sales, transportation and distribution,

Table 7.1 Global WF within Different Water-Using Categories during 1996–2005

Economic Sector	Water Use Category	Global WF (10^9 m^3/year)					Remark
		Green	Blue	Gray	Total	%	
Primary sector	Crop farming	5,771	899	733	7,404	81.5	
	Pasture	913	–	–	913	10.0	
	Animal farming	–	46	–	46	0.5	Water for drinking and cleaning
	Agriculture total	6,684	945	733	8,363	92.0	
	Aquaculture	?	?	?	?	?	No global data
	Forestry	?	?	?	?	?	No global data
	Mining, quarrying	?	?	?	?	?	No global data
Secondary sector	Industry (self-supply)	–	38	363	400	4.4	Water use in manufacturing, electricity supply, and construction
	Municipal water supply	–	42	282	324	3.6	Water supply to consumers and (small) users in primary, secondary, and tertiary sectors
Tertiary sector	Self-supply	?	?	?	?	?	No global data
Consumers	Self-supply	?	?	?	?	?	No global data
	Total	6,684	1,025	1,378	9,087	100	

Note that the blue WF figure for crop farming relates to evapotranspiration of irrigation water at field level; it excludes losses from storage reservoirs and irrigation canals. The blue WF figure for "industry" presented here includes water use in mining, which is part of the primary sector. The figure excludes water lost from reservoirs for hydroelectric generation. All gray WF figures are conservative estimates. Forestry is not included as a water use sector because of a lack of data.
From Mekonnen and Hoekstra (2011) for crop farming; Mekonnen and Hoekstra (2012) for pasture and animal farming; Hoekstra and Mekonnen (2012) for industry and municipal water supply.

entertainment, restaurants, clerical services, media, tourism, insurance, banking, health care, defense, and law. Even though sometimes categorized into another quaternary sector, one can also list activities related to government, culture, libraries, scientific research, education, and information technology. The secondary and tertiary sectors have much smaller WFs than the primary sector.

It is difficult to get water use statistics organized along the same structure of economic sector classifications. Many countries and regions have their own classification of economic activities, distinguishing main sectors and subsectors. One of the international standard classifications is the Industrial Classification of All Economic Activities of the United Nations (UN, 2008). Conventional water use statistics mostly show gross blue water withdrawals and distinguish three main categories: agricultural, industrial, and municipal water use (FAO, 2014). WF statistics also distinguish between the agricultural, industrial, and municipal sector. These three sectors cannot be mapped one-to-one onto the primary, secondary, and tertiary sector. "Agricultural water use" obviously is about water use in the primary sector, whereas "industrial water use" is about water use in the secondary sector. However, water use in mining—part of the primary sector—will generally be categorized under "industrial water use" as well. Industrial water use refers to self-supplied industries not connected to the public distribution network. It includes water for the cooling of thermoelectric plants, but it does not include hydropower (which is often left out of the water use accounts altogether). Municipal water use—often alternatively called domestic water use or public water supply—refers to the water use by water utilities and distributed through the public water distribution network. Water utilities provide water directly to consumers, but also to water users in the primary, secondary, and tertiary sector.

The mismatch between the three main categories in water use statistics and the different sectors as usually distinguished in the economy can be quite confusing. The "water supply sector" as distinguished in economic classifications refers to water utilities delivering municipal water to households and others connected to the public water supply system. Unfortunately, the category of municipal water use lumps water use for a great variety of water users: final consumers (households) and users in all economic sectors. Specifications by type of user are not always available. Additionally confusing is that even though the "water supply sector" serves all types of users, the sector refers to only a minor fraction of total water use. Most of the water use in agriculture, the largest water user, is not part of the "water supply sector." Furthermore, water self-supply by industries does not fall within this sector, and neither does self-supply in the tertiary sector or self-supply by final consumers. Given that only an estimated 3.6% of the total WF of humanity relates to what we call the "water supply sector" (Hoekstra and Mekonnen, 2012), the sector receives disproportionate attention in public debates about water use and scarcity, diverting the necessary attention to water use in agriculture and industry.

An additional problem is that the contribution of agriculture to water scarcity is underestimated by conventional water use statistics, which show gross blue water abstractions. In agriculture, most of the gross water use will evaporate from storage reservoirs, irrigations canals, or from the field. The water abstracted for irrigation in agriculture is thus largely unavailable for reuse within the basin. In industrial water use, the ratio of net to gross abstraction is estimated at less than 5%. In municipal water use, this ratio varies from 5% to 15% in urban areas and from 10% to 50% in rural areas (FAO, 2014). Water that returns to the catchment after use can be reused. Presenting gross or net water abstractions thus makes a huge difference for industries and households and less of a difference in agriculture.

Even though the primary sector is the largest water user, governmental programs to create public awareness of water scarcity often focus on public campaigns calling for water-saving at home. This is not very effective at large given the fact that the major share of water use in most places relates to agriculture and, secondarily, to industry. Water scarcity is thus generally caused mostly by excessive water use in agriculture. Installing water-saving showerheads and dual-flush toilets in households will have barely any impact on mitigating water scarcity, but still this is what most water-saving campaigns advocate. It would be more useful to make people aware of the water use and pollution underlying the food items and other products they buy and to advocate product labels that show the sustainability of the WF of a product.

AGRICULTURE, FISHING, AND FORESTRY

The WF in the agricultural sector has been studied in great detail by a variety of authors. Most studies focus on the WF of crops. The first global study of green–blue WFs of crops per country was performed by Hoekstra and Hung (2002), followed by a study by Hoekstra and Chapagain (2007). The first global grid-based study was performed by Rost et al. (2008), who applied the LPJmL model. Later grid-based studies include those by Liu and Yang (2010), who used the GEPIC model; Siebert and Döll (2010), who used the GCWM model; Hanasaki et al. (2010), who applied the H08 model; and Fader et al. (2011), who used the LPJmL model again. The different studies were performed with different models, but for partially different periods and using different underlying land, soil, climate, and crop data as well, so it is difficult to compare the results. The study by Mekonnen and Hoekstra (2011) is the only global grid-based study that includes an assessment of the gray WF of crops. Fewer studies address the WF of animal products. The first global study was by Chapagain and Hoekstra (2003), who distinguished eight animal groups, three farming systems (grazing, mixed, industrial), and different feed composition per animal group, farming system, and country. Oki and Kanae (2004) published data for Japan, and Pimentel et al. (2004) published data for the United States. The best global dataset currently available is that provided by Mekonnen and Hoekstra (2012); it has the same details as the study by Chapagain and Hoekstra (2003) but also includes gray WFs and follows a number of methodological improvements. General findings are that WFs of both crops and livestock products show a great variation depending on production circumstances and that, in general, the WF per kilogram or kilocalorie is smaller for crops than for animal products (Table 7.2). In the case of animal products, the feed conversion efficiency, feed composition, and feed origin are the most important determinants (Hoekstra, 2012).

Table 7.2 The Global Average WF of Some Selected Food Products

		WF per kg (L/kg)				Nutritional Content			WF per Unit of Nutritional Value		
Origin	**Food Item**	**Green**	**Blue**	**Gray**	**Total**	**Calorie (kcal/kg)**	**Protein (g/kg)**	**Fat (g/kg)**	**Calorie (L/kcal)**	**Protein (L/g protein)**	**Fat (L/g fat)**
Vegetable origin	Sugar crops	130	52	15	197	285	0.0	0.0	0.69	0.0	0.0
	Vegetables	194	43	85	322	240	12	2.1	1.34	26	154
	Starchy roots	327	16	43	387	827	13	1.7	0.47	31	226
	Fruits	726	147	89	962	460	5.3	2.8	2.09	180	348
	Cereals	1,232	228	184	1,644	3,208	80	15	0.51	21	112
	Oil crops	2,023	220	121	2,364	2,908	146	209	0.81	16	11
	Pulses	3,180	141	734	4,055	3,412	215	23	1.19	19	180
	Nuts	7,016	1,367	680	9,063	2,500	65	193	3.63	139	47
Animal origin	Milk	863	86	72	1,020	560	33	31	1.82	31	33
	Eggs	2,592	244	429	3,265	1,425	111	100	2.29	29	33
	Chicken	3,545	313	467	4,325	1,440	127	100	3.00	34	43
	Butter	4,695	465	393	5,553	7,692	0.0	872	0.72	0.0	6.4
	Pork	4,907	459	622	5,988	2,786	105	259	2.15	57	23
	Sheep/goat meat	8,253	457	53	8,763	2,059	139	163	4.25	63	54
	Beef	14,414	550	451	15,415	1,513	138	101	10.2	112	153

Source: From Mekonnen and Hoekstra (2012).

The WF of fish primarily depends on four factors: the type of water in which it grows (saltwater, brackish water, or freshwater systems); whether it lives in natural waters or is cultivated in aquaculture; its feed composition and origin; and its feed conversion efficiency. A saltwater fish naturally feeding itself, not cultivated but caught in open water, does not have any freshwater footprint. This is not to say that this fish may not be accompanied by other environmental concerns (like overfishing, problems related to bycatch, and damage caused by fishing techniques applied), but it means that this fish puts no claims on the limited global freshwater resources. The WF of this fish available at the retailer will refer only to the WF of materials and energy involved in fishing, transport, and packaging. This WF is small when compared with the WF that fish can have when fed with land-based and, thus, freshwater-based feed. According to Naylor et al. (2009), the range of plant feedstuffs in aquafeeds currently includes barley, rapeseed, maize, cottonseed, peas/lupines, soybean, and wheat. The ratio of plant-based protein in aquafeeds is increasing, so the question about the WF of fish becomes increasingly relevant. Fish grown in open ponds also have a WF related to the evaporation losses from those ponds.

With an average feed conversion efficiency of approximately 2 (i.e., 2 kg of feed per kg of fish), fish is more efficient than chicken, so the feed-related WF of fish will generally be lower than that of chicken, even with very high fractions of plant-based material in the aquafeeds. Fish grown in open ponds, however, will additionally have a blue and gray WF related to evaporation and water pollution from those ponds. According to Verdegem et al. (2006), a fish pond with evaporation plus seepage losses of 3,500 mm/y and an annual production of 1,000 kg/ha/y loses 35 m^3 of water through evaporation and seepage per kilogram of fish produced. If the pond is drained and filled once per year, then total water consumption equals 45 m^3/kg of fish produced. The blue WF will be smaller, however, because only the evaporation counts as consumptive water use. This will be of the order of 1,000–2,000 mm/y, depending on climatic conditions, and thus implies a blue WF of 10–20 m^3/kg of fish. An important factor is the fish production per hectare. The previously mentioned 1,000 kg/ha/y refers to extensive systems; in intensively mixed systems, the productivity can be 100 times higher, and the blue WF per kilogram of fish related to open-pond evaporation thus can be 100 times smaller (100–200 L/kg). Water from fish ponds is generally highly polluted, thus causing a gray WF. No estimates of that are available yet.

Regarding the WF of wood, Van Oel and Hoekstra (2012) found WFs of harvested wood varying between 200 and 1,100 m^3 of water per m^3 of wood. The global average found is approximately 500 m^3/m^3. Important determinants are the evapotranspiration rate of a production forest (in mm/year) and the average wood yield (in m^3) per hectare per year. The former depends on climate and tree species, and the latter depends on tree species and forestry practice. Eucalyptus is a fast-growing, thus high-yielding, species, but grows in warmer climates with high evapotranspiration rates.

MINING AND QUARRYING

Mining is the process of extracting buried material below the earth surface. Quarrying refers to extracting materials directly from the surface. In mining and quarrying, water is used and gets polluted in a range of activities, including mineral processing, dust suppression, and slurry transport. In addition, water is subtracted from the environment in the process of dewatering, the process of pumping away the water that naturally flows into the pit or tunnels of the mine. When disposed, this water may also carry pollutants. The mining and quarrying sector includes mining of fossil fuels (coal and lignite mining, oil and gas extraction), mining of metal ores, quarrying of stone, sand, and clay, and mining of phosphate and other minerals. A rich data source of water use in the mining of conventional and unconventional oil and gas, coal, and uranium is provided in the work of Williams and Simmons (2013).

Mudd (2008) provides a useful review of gross blue water use in different types of mining (Table 7.3). In general, he found that the higher the ore throughput, the more likely that, through economies of scale, the unit water use per kilogram of ore is lower. Furthermore, he found that as metallic ore grades decline, there is a strong probability of an increase in water use per unit of metal. Gold has the highest water use per kilogram of metal, with platinum closely behind; this is presumably attributable to the very low grade of gold and platinum ores (i.e., parts per million compared with percent for base metals). It is noted here that net blue water use, the blue WF, will be substantially lower than the figures presented in Table 7.3, because most of the water will remain within the catchment.

Table 7.3 Gross Blue Water Use in Mining

	Gross Blue Water Use Per Unit of Ore Throughput		**Gross Blue Water Use Per Unit of Ore Grade**	
Mineral/Metal	**Average**	**SD**	**Average**	**SD**
Bauxite (L/kg bauxite)	1.09	0.44	–	–
Black coal (L/kg coal)	0.30	0.26	–	–
Copper (L/kg ore; L/kg Cu)	1.27	1.03	172	154
Copper–gold (L/kg ore; L/kg Cu)	1.22	0.49	116	114
Diamonds (L/kg ore; L/carat)	1.32	0.32	477	170
Gold (L/kg ore; L/kg Au)	1.96	5.03	716,000	1,417,000
Zinc ± lead ± silver ± copper ± gold (L/kg ore; L/kg Zn ± Pb ± Cu)	2.67	2.81	29.2	28.1
Nickel (sulfide) (L/kg ore; L/kg Ni)	1.01	0.26	107	87
Platinum group (L/kg ore; L/kg PGM)	0.94	0.66	260,000	162,000
Uranium (L/kg ore; L/kg U3O8)	1.36	2.47	505	387

The figures refer to the sum of water abstractions and recycling volumes. SD = standard deviation.
Source: From Mudd (2008).

Peña and Huijbregts (2014) made a detailed estimate of the operational and supply chain blue WF for the extraction, production, and transport to the nearest seaport of high-grade copper refined from two types of copper ore—copper sulfide ore and copper oxide ore—in the Atacama Desert of northern Chile, one of the driest places on earth. The total blue WF (direct and upstream consumption) for the sulfide ore refining process was 96 L/kg of copper cathode. The first step in the process, the extraction from the open pit mine, accounts for 5% of the total blue WF; the second step, comminution (crushing, grinding), accounts for 3%; the third step, the concentrator plant, accounts for 59%; the fourth step, the smelting plant, contributes 10%; and the last two steps, electrorefinery and the sulfuric acid plant, contribute 3% and 1%. The supply chain contributes 19%: approximately 9% related to materials and 10% related to electricity. In the case of the copper oxide ore-refining process, the blue WF was 40 L/kg of copper cathode. The first step, extraction, accounts for 2%; the second step, comminution and agglomeration, contributes 18%; the third step, the heap leaching process, accounts for 44%; the fourth step, solvent extraction, contributes nothing; and the last step, electrowinning, accounts for 10%. The supply chain contributes 26%: approximately 6% related to materials and 20% related to electricity.

Generally, mining has a significant gray WF, but it is difficult to obtain quantitative data for this. The first source of pollution can come from the "overburden," the waste soil and rock that has to be removed before the ore deposit can be reached and that has to be stored somewhere after removal. The "strip ratio", the ratio of the quantity of overburden to the quantity of mineral ore extracted, can be much higher than one. The overburden material, sometimes containing significant levels of toxic substances, is usually deposited on-site in piles on the surface or as backfill in open pits, or within underground mines (ELAW, 2010). Through erosion, runoff, and seepage, these toxic substances may reach groundwater or surface water bodies. The second source of pollution comes from the pit itself, where similar processes may spread toxic chemicals into the wider environment. In addition, mine dewatering can bring polluted water from the mine to the streams into which the water is released. The third source of pollution comes from the waste material that remains after concentration of the valuable mineral from the extracted ore and that often contains various toxic substances (like cadmium, lead, and arsenic). This waste, the so-called tailings, is generally stored in tailings ponds, which may leak. Also, there are numerous incidents of tailings reservoir dam breaks, after which the content of the reservoir released itself into the environment. A fourth source of pollution can come from the process of heap leaching. With leaching, finely ground ore is deposited in a large pile (called a "leach pile") on top of an impermeable pad, and a solution containing cyanide is sprayed on top of the pile. The cyanide solution dissolves the desired metals and the "pregnant" solution containing the metal is collected from the bottom of the pile using a system of pipes, a procedure that brings significant environmental risk (ELAW, 2010). Finally, a form of mining that typically results in significant water pollution is the so-called placer mining, in which bulldozers, dredges, or hydraulic jets of water are used to extract the ore from a stream bed or flood plain (ELAW, 2010). Placer mining is a common method to obtain gold from river sediments.

MANUFACTURING

The manufacturing sector is the most diverse of all economic sectors. I reflect on the WF of just a few specific subsectors: food and beverage; textile and apparel; paper; computers; and motor vehicles.

Food and beverage products

The food and beverage sector is the manufacturing sector with the largest WF (maybe not the largest operational WF, but definitely the largest supply chain WF). The reason is that the food and beverage sector is the largest client of the agricultural sector, which is responsible for the largest share in global water consumption (Table 7.1). WF studies performed in the beverage sector include the studies performed by SABMiller (SABMiller and WWF-UK, 2009; SABMiller, GTZ and WWF, 2010), Coca-Cola (TCCC and TNC, 2010; Coca-Cola Europe, 2011) and the Beverage Industry Environmental Roundtable (BIER, 2011). Some good examples of WF studies in the food sector include those regarding Unilever (Jefferies et al., 2012), Dole (Sikirica, 2011), Mars (Ridoutt et al., 2009), and Barilla (Ruini et al., 2013).

Traditionally, the beverage industry focuses on the so-called water use ratio (WUR), which is defined as the total water use divided by the total production at a bottling facility, expressed in terms of liter of water used per liter of beverage produced. Water use here represents gross blue water abstraction, not net blue water abstraction (blue WF). In a global benchmarking study for the period 2009–2011, BIER (2012) reported a WUR of 1.2–2.2 L/L (with an average of 1.5) for bottled water, a WUR of 1.5–4.0 (average 2.1) for carbonated soft drinks, a WUR of 3.2–6.6 (average 4.3) for beer breweries, a WUR of 8–126 (average 36) for distilleries, and a WUR of 2.0–18.5 (average 4.4) for wineries. The WUR is of limited value because the operational WF of bottling factories is very small when compared with the full WF of a beverage, as shown by Ercin et al. (2011) regarding carbonated soft drinks. They showed that the WF of a half-liter bottle of a soft drink resembling cola can range between 150 and 300 L, of which 99.7–99.8% refers to the supply chain.

Textile and apparel

According to Wang et al. (2013), the blue operational WF of the People's Republic of China's textile industry was, on average, 0.8×10^9 m^3/y during the period 2001–2010 (increasing over time from 0.5 to 1.0×10^9 m^3/y). Based on the loads of COD (chemical oxygen demand) to freshwater, accounting for the treatment of wastewater before disposal, they compute a gray WF of approximately

10×10^9 m^3/year on average during the same period (again increasing over time). Without current levels of treatment, the gray WF would have been five times larger. The gray WF calculation was based on a maximum acceptable biochemical oxygen demand (BOD) of 100 mg/L in textile effluents and the assumption of zero background concentrations in the receiving water bodies. Using the effluent standard as a reference leads to an underestimation of the gray WF, because effluent standards are generally less strict than ambient water quality standards. Gray WF guidelines of WFN, for example, recommend an ambient water quality standard for COD of 30 mg/L (Franke et al., 2013). The assumption of zero background concentrations leads to an overestimation of gray WF, because natural concentrations of COD are not zero. The figures reported by Wang et al. (2013) are totals for three subsectors: manufacture of textiles; manufacture of textile apparel, footwear, and hats; and manufacture of chemical fibers. The manufacture of textiles contributed the largest part to the gray WF of the textile sector as a whole. The gray WF per unit of output value of the textile manufacturing industry decreased from 70 to 20 L/USD.

Chico et al. (2013) estimated the WF of a pair of jeans made in Spain (assuming a weight of 780 g per pair of trousers) by considering two different fibers (cotton and Lyocell fiber) and five different production methods for spinning, dying, and weaving. Including water use in the full supply chain (cotton growing for cotton lint and wood growth for Lyocell fibers), they reported a total WF of 2,800–4,900 L for one pair of cotton trousers (on average 8% green, 86% blue, and 6% gray WF) and a total WF of 1,200–1,900 L for one pair of Lyocell trousers (on average 95% green, 2% blue, and 2% gray WF). In the case of cotton trousers, cotton-growing contributed the largest share to the total, whereas for Lyocell trousers it was the growing of the wood that contributed the largest share. Cotton-growing often heavily relies on irrigation and, therefore, blue water (Chapagain et al., 2006), and wood relies mainly on green water. The WF of wood mainly varies depending on the origin of the wood and forest type (Van Oel and Hoekstra, 2012). According to Chico et al. (2013), ginning of cotton had a blue WF of 30–60 L/kg and a zero gray WF, whereas spinning and weaving had a blue WF of 54–134 L/kg and gray WF of 0–0.06 L/kg. Lyocell fiber production from pulp would have a blue WF of 1 L/kg and a gray WF of 4–272 L/kg, whereas spinning and weaving would have a blue WF of 105 L/kg and a gray WF comparable with that for the case of cotton.

There can be large differences in the supply chain WF of the textile and apparel sector, depending on the type of fibers used and the source region of the fibers. The WF of cotton fibers is substantially larger than most other plant fibers. To honestly compare, we can compare cotton lint, which is the cotton fiber separated from the cottonseed, with other plant fibers (Hoekstra, 2013). According to Mekonnen and Hoekstra (2011), the global average WF of seed cotton is 4,030 L/kg (the sum of green, blue, and gray). The seed cotton is split into cottonseed (63% of the weight, 21% of the economic value) and cotton lint (35% of the weight, 79% of the economic value). The WF of the cotton lint thus can be calculated as $(0.79/0.35) \times 4{,}030 = 9{,}100$ L/kg. In the process from cotton lint to final

Table 7.4 Global Average WF of Different Plant Fibers during 1996–2005

	Global Average WF (L/kg)			
Product	**Green**	**Blue**	**Gray**	**Total**
Abaca fiber	21,529	273	851	22,654
Cotton lint	5,163	2,955	996	9,113
Sisal fiber	6,791	787	246	7,824
Agave fiber	6,434	9	106	6,549
Ramie fiber	3,712	201	595	4,507
Flax fiber	2,866	481	436	3,783
Hemp fiber	2,026	0	693	2,719
Jute fiber	2,356	33	217	2,605

Source: From Mekonnen and Hoekstra (2011) and from Hoekstra (2013).

cotton fabric, there are again some weight losses and by-products, so that the WF of cotton fabric is again a bit larger. In this way, we arrive at 10,000 L/kg. For the purpose of a fair appraisal, we can compare WFs in L/kg either at the level of the fibers or at the level of the final textile. For the outcome it will make little difference, because the big differences in water use are in the growth of the plants, not in the water use for processing of fibers into final textile. Here, we compare the WF of cotton lint with the WF of the fibers of other plants. An overview is given in Table 7.4. From this overview, it is clear that, on average, the WF of cotton fibers is a bit larger than the WF of sisal and agave fibers, much larger than that of ramie and flax fibers, and very much larger than the WFs of hemp and jute fibers. We should be careful to immediately conclude that we should replace cotton fibers by, for example, hemp fibers, because fibers are different and textiles made from different fibers have different characteristics. However, it shows that it is worth investigating how cotton compares with hemp and other fibers in other respects and to what extent and in which applications cotton can be substituted by other plant fibers. It would also make sense to compare the performance of plant fibers with animal fibers (like different types of wool) and synthetic fibers (often made from petroleum), whereby, again, the claim on water resources of a fiber can be just one of a more extended set of criteria.

Paper

The WF of any wood product is the sum of the WFs in the forestry and the industrial stage. We focus here on the pulp and paper industry. A pulp mill converts wood chips or other plant fiber sources into thick fiberboard that can be shipped to a paper mill for further processing into final paper products. The blue WF in the industrial stage can be estimated by summing the evaporation flows from the pulp and paper mills, the amount of water incorporated in the products delivered by the mills, and the volume of water contained in solid residuals (Hoekstra, 2013).

The gray WF depends on the loads of different chemicals contained in the mill effluents discharged into the environment. Paper industries are known for their large water demand and for producing polluted effluents, which, if not properly treated, can cause significant ecological damage in the streams into which the effluents are disposed. The pulp and paper industry in the United States withdraws approximately $5{,}500 \times 10^9$ L of water annually from surface and groundwater sources (NCASI, 2009). A major part of the water used, however, returns to the catchments from where the water has been taken, so that consumptive water use is much less than total abstraction: an estimated volume of 507×10^9 L of water annually evaporates from pulp and paper mills in the United States, and 10×10^9 L of water leaves the mills (and the catchments) incorporated in products. Probably more important than the consumptive use of water in pulp and paper mills is the pollution that comes from those mills. Although mechanical pulping is applied as well, chemical pulping is the most commonly used pulping process. Chemical pulps are made by cooking the raw materials and adding a mixture of chemicals. After pulping, the pulp is generally bleached to make it whiter. Different sorts of chemicals are used in this process, including, for example, chlorine, sodium hypochlorite, and chlorine dioxide. The use of elemental chlorine or chlorine compounds particularly results in high concentrations of undesired compounds in effluents. Water pollution from pulp and paper mills mostly stems from the organic matter contained in the effluents, which generally include several chlorinated organic compounds like dioxins and other adsorbable organic halides (usually abbreviated as AOX). The organic matter content in effluents from pulp and paper mills is measured by the BOD in the effluent; a large BOD in effluents can lead to oxygen depletion and fish kills in rivers. High concentrations of AOX can also lead to toxicity and fish kills. According to Hoekstra (2013), the WF for one final A4 sheet of copy paper (80 g/m^2) ranges from 2 to 20 L of water, which covers the water use in both the forestry and industry stages. The two major variables that influence the size of the WF of paper and that can be relatively easily influenced are the paper recycling rate and the amount of chemicals in effluents discharged into the environment (Hoekstra, 2013).

As an example, we discuss a study by the UPM-Kymmene Corporation, a Finnish pulp, paper, and timber manufacturer. They assessed the operational and supply chain WF of their Nordland paper mill in Germany (Rep, 2011). The majority of chemical pulp used at this paper mill comes from three pulp mills: the Kaukas and Pietarsaari pulp mills in Finland and the Fray Bentos pulp mill in Uruguay. In the Finnish pulp mills, three different types of tree are used: broadleaves, pine, and spruce. In the pulp mill in Uruguay, eucalyptus trees are used as the raw resource. The Nordland paper mill in Germany produces two paper grades: wood-free coated paper (150 g/m^2) and wood-free uncoated paper (80 g/m^2). Wood-free paper is paper made from chemical pulp instead of mechanical pulp. Chemical pulp is made from pulpwood and is considered wood-free because most of the lignin is removed and separated from the cellulose fibers during processing, in contrast to mechanical pulp, which retains most of its wood components and therefore can still be described as wood-containing. It was found that the total WF of one A4 sheet of paper leaving the Nordland paper mill is 13 L for wood-free uncoated paper and 20 L for wood-free coated paper. The color composition of that total WF is 60% green, 39% gray, and 1% blue. Approximately 99% of the total WF originates from the raw material supply chain (forestry stage and pulp mills in Finland and Uruguay) and the remaining 1% originates from the production processes within the Nordland paper mill in Germany. The gray WF assessment showed that AOX was the most critical indicator from an environmental impact perspective, requiring the biggest volume of water to dilute to acceptable concentrations.

Computers

The semiconductor manufacturing process requires high-purity water, which is generally produced on-site from municipal water. For the fabrication of a silicon wafer, Williams et al. (2002) reported water use figures between 5 and 58 L/cm^2 of silicon. With a typical value of 20 L/cm^2 and a surface of 1.6 cm^2, this means that producing a single 2-g 32-MB DRAM (dynamic random access memory) chip requires 32 L per chip in the fabrication stage.

In a life cycle study of personal computers for Hewlett-Packard, Alafifi (2010) estimated the blue water use of a desktop computer at 10,000 L, 59% of which would relate to electricity in the use stage of the computer (assuming a life span of 5 years). Approximately 34% was related to manufacturing of the components (22% for producing the LCD monitor, 8% for manufacturing printed circuit boards, and 3% for fabrication of semiconductors), 7% was related to the extraction of raw materials, and 1% was related to assembly. It is noted that different electricity generation mixes have significant influence on the total water use due to the different water use intensities of various energy sources. A major drawback of the water use figures presented by Alafifi (2010) is that it remains unclear how to interpret the numbers, which is typical for present-day studies of water use in industry. Sources of data are often unclear about whether water use figures refer to gross water use or consumptive water use. In practice, many studies use the terms “water use” and “water consumption” interchangeably, but both generally refer to gross water use. Even though Alafifi (2010) presented 10,000 L for a desktop computer as the “blue WF” of the personal computer, most of the underlying data used probably refer to gross water use, not consumptive water use, which makes a great difference.

Regarding computer monitors, Socolof et al. (2001) studied the life cycle impacts of desktop computer displays and found water use of 13,100 L per CRT (cathode ray tube) and 2,820 L per LCD (liquid crystal display).

Motor vehicles

A number of car companies have performed WF studies, but little has been made publicly available. An interesting public report is one regarding the WF of a few facilities of TATA Motors in India for the year 2012 (Unger et al., 2013). Tata Motors has approximately 1,000 suppliers, accounting for the majority of its overall WF. The highest inside-the-fence water consumption in the facilities studied was from the paint shop and forging. Among the facilities, the largest direct blue WF was found for a facility in Lucknow in the state of Uttar Pradesh that produces heavy and medium commercial vehicles, mainly buses, with 5.5 m^3 per equivalent vehicle. The base model used for equivalent vehicle calculations was the 1,612 (load-bearing capacity of 16 tons, 120 hp). In Pune, in the state of Maharashtra, the direct blue WF was 4.75 m^3 per equivalent vehicle, again with the 1,612 as the base model, and in Jamshedpur, in the state of Jharkhand, it was 3.3 m^3 per equivalent vehicle with the same base model. In Pantnagar, in the state of Uttarakhand, the direct blue WF was 4.9 m^3 per equivalent vehicle, this time with the ACE Goods Carrier as the base model, which is a 1-ton mini-truck. The smallest direct blue WF was found in another facility in Pune that produced passenger cars, with 1.7 m^3 per equivalent vehicle and with the Tata Indica diesel as the base model for the equivalent calculations. Direct gray WFs were smaller than the blue WFs in the six facilities studied. For the heavy vehicles, the direct gray WF varied from 2.9 m^3 per equivalent vehicle in Jamshedpur and 2.4 m^3 in Pune to 0.4 m^3 in Lucknow. For the mini-trucks from Pantnagar, the gray WF was 2.0 m^3 per equivalent vehicle. For the passenger cars from Pune, the direct gray WF was 0.7 m^3 per equivalent vehicle. The number of parameters included in the gray WF calculations varied, with up to nine parameters. In all cases, effluents are treated before disposal.

Another interesting study is one by Berger et al. (2012) regarding the blue WF of three car models of Volkswagen over their full life cycle. They estimated that the water consumption along the life cycles of the three cars studied amounts to 52 m^3 (Polo 1.2 TDI), 62 m^3 (Golf 1.6 TDI), and 83 m^3 (Passat 2.0 TDI). In all three cases, 95% of the total water consumption lies in the production stage of the car (as opposed to the use and end-of-life stages). In the case of the Golf 1.6 TDI, the largest contributions to the total life cycle water consumption come from steel and iron (approximately 34%), polymers (another 34%), and precious metals like gold, silver, and platinum (20%). The latter figure is high given the fact that it takes less than 1 kg of precious metals per car. The reported figure for precious metals is probably an overestimate because the study assumed 100% primary material, and Volkswagen has been operating a catalyst recycling program for years, which helps to recover and recycle PGM in a closed-loop system. Water consumption for manufacturing, the final assembly, was 0.36 m^3 per car. Apart from the water consumption for final assembly, there was also water consumption at the car production sites for other activities, like injection moulding of polymer components and hot stamping of steel components. Altogether, approximately 10% of the total life cycle water consumption occurs directly at the car production sites in Pamplona, Wolfsburg, and Emden, mainly resulting from painting and evaporation of cooling water.

WATER SUPPLY

One would expect that the WF of the "water supply" sector is most significant of all sectors, but this is not the case. On a global level, the WF of the municipal water supply has been estimated to be 3.6% of the total WF of humanity (Table 7.1). Wuppertal Institute (2011) reports a material intensity factor for drinking water of 1.3 L/L, referring to gross blue water use. As noted, the ratio of net to gross abstraction has been estimated to be 5−15% in urban areas and 10−50% in rural areas (FAO, 2014). This means that the blue WF of drinking water from the tap can be as little as 0.065 L/L, or 0.65 L/L in the worst case, assuming that the rest of the water returns to the water system from which it was abstracted. The gray WF related to municipal water supply depends on the extent of treatment of the wastewater. The gray WF of municipal water supply will generally be larger than the blue WF, even in the case of treatment before disposal, because the concentrations of nitrogen, phosphorous, and other substances in the wastewater after treatment will still be beyond the concentrations in the intake water (Figure 7.2).

CONSTRUCTION

The direct WF of the construction industry is small compared with the indirect WF related to the mining and manufacturing of materials used in construction. McCormack et al. (2007) illustrate this with a number of Australian nonresidential case studies using an input−output-based hybrid embodied-water analysis. Regarding the water embodied in construction, they found values between 5 and 20 m^3 of water per m^2 of gross floor area. The lower values represented refurbishment projects rather than complete new construction projects. According to this study, steel had the largest contribution in this total of embodied water, followed by concrete. Carpet had the third largest contribution, which is important because it is often replaced every 10 years or even more frequently in prestigious commercial buildings. The direct water use in the construction process was small compared with the total, maximally 1 m^3 of water per m^2 gross floor area. It has to be noted that the figures cited here refer to gross blue water use, not net consumptive water use (blue WF).

TRANSPORT

Transport is always considered an important sector in carbon footprint assessment, because transport can significantly contribute to the overall carbon footprint of a final product, measured over its full supply chain. In the case of the WF of a final product, the contribution of transport will generally be relatively small, because not much freshwater is being consumed or polluted during transport. It is worth considering the indirect WF of transport related to materials (trucks, trains, boats, airplanes) and energy used, but materials will generally contribute very little because the WF of a transport vehicle can be distributed over all goods transported over the lifetime of the vehicle. The WF of energy may be more relevant, but even that can be small compared with the other components of the WF of goods, particularly in the case of agricultural goods. The key determinant in the WF of transport is probably the energy source (King and Webber, 2008; Gerbens-Leenes et al., 2009a). The WF of bioenergy in terms of cubic meter per GJ is generally two to three orders of magnitude larger than that for energy from fossil fuels or wind or solar power. However, in all energy categories, WFs per unit of energy can widely vary, depending on the precise source and production technology. The technique of hydraulic fracturing (fracking) to mine natural gas or petroleum reserves, for example, has a larger blue and gray WF than that for mining reserves that are more easily accessible using more conventional techniques. In the case of bioenergy, it matters greatly whether one speaks about biodiesel from oil crops, bioethanol from sugar or starch crops (Gerbens-Leenes et al., 2009b; Dominguez-Faus et al., 2009), biofuel from cellulosic fractions of crops or waste materials (Chiu and Wu, 2012), or bioelectricity. In the latter case, it makes a large difference what is burned, for example biomass grown for the purpose or organic waste. As an illustration of the large differences between different bioenergy forms, Table 7.5 gives the WF of different modes of passenger and freight transport when based on first-generation biofuel produced in the European Union. Governmental policies to replace substantial percentages of fossil fuels by biofuels will lead to a rapid growth of the WF of the transport sector (Gerbens-Leenes et al., 2012).

WHOLESALE, RETAIL TRADE, AND SERVICES

There has been little investigation regarding the WF of the wholesale, retail trade, and services sectors. The reason is that the direct WF of these sectors will be generally small compared with their indirect WF, i.e., the WF of the goods bought for use or sale. Particularly in the wholesale and retail trade sectors, all that matters is the WF of the goods purchased to sell. Wholesale and retail companies can play an important role in WF reduction, not because of the significance of their operational WF but rather because they form a point where many products from a great number of producers come together to be distributed over a large number of consumers. Wholesale companies and retailers can influence the WF of the products on their store shelf by using sustainability criteria in their purchasing choices.

In the service sector, the major determinant in the total WF will generally be the WF related to consumables, like paper, computers, printers, machineries, vehicles, other materials, and energy. The WF of the construction materials of office buildings may play a minor role. One component will often dominate: the food served in the company restaurant, even though this is obviously not part of the primary business of a company. As an example, we discuss here a study by Factor-X, an environmental consultancy firm in Belgium, which was one of the first companies in the service sector to estimate its operational and supply chain

Table 7.5 The WF of Different Modes of Passenger and Freight Transport When Based on First-Generation Biofuel Produced in the European Union

Transport Mode	Energy Source	Green + Blue WF of Passenger Transport (L/passenger km)	Green + Blue WF of Freight Transport (L/1,000 kg of freight per km)
Airplane	Biodiesel from rapeseed	142–403	576–1,023
	Bioethanol from sugar beet	42–89	169–471
Car (large)	Biodiesel from rapeseed	214–291	–
	Bioethanol from sugar beet	138–289	–
Car (small)	Biodiesel from rapeseed	65–89	–
	Bioethanol from sugar beet	24–50	–
Bus/lorry	Biodiesel from rapeseed	67–126	142–330
	Bioethanol from sugar beet	20–58	–
Train	Biodiesel from rapeseed	15–40	15–40
Ship (inland)	Biodiesel from rapeseed	–	36–68
Ship (sea, bulk)	Biodiesel from rapeseed	–	8–11
Electric train	Bioelectricity from maize	3–12	2–7
Electric car	Bioelectricity from maize	4–7	–
Walking	Sugar from sugar beet	3–6	–
Bike	Sugar from sugar beet	1–2	–

The total WF of transport based on first-generation biofuel mainly relates to the water volumes consumed in growing the crop.
Source: From Gerbens-Leenes and Hoekstra (2011).

WF. The scope of the study included both direct and indirect water use during the approximate 225 work days during the year 2011 (Factor-X, 2011). The study included food consumption by employees and the use of electricity for computers and internet, telephones, paper for printing, and office equipment. The study did not include domestic and international travel, clothing, and use of mobile phones, or the construction of the office. The direct blue, green, and gray WFs were estimated at 115, 4, and 320 L/employee per work day, respectively. The gray WF referred to the pollution from organic matter in the wastewater. The indirect blue–green WF related to food was estimated at 3,420 L/employee per work day, the indirect blue WF related to professional activities (heating of the building, paper, electricity use, etc.) was estimated to be 140 L, and the indirect blue WF related to the manufacture of office equipment (computers, printers, desks, chairs, cupboards, lockers, plastic) was estimated to be 5 L/employee per work day. Factor-X concluded that the WF related to food consumption of their workers is dominant over their direct operational WF or their indirect WF related to energy use or office equipment, and that promoting vegetarian food among their workers is probably the most effective measure. However, the company recognizes other measures, like using dry toilets, moving to a paperless office, and reducing energy consumption. Also, it was noted that improved wastewater treatment in the country would help.

WATER STEWARDSHIP AND TRANSPARENCY

There is an increasing call for good water stewardship and transparency in the private sector that is driven by increased public awareness, demands from investors, and perceived water risks by the sector itself. Water stewardship is a comprehensive concept that includes the evaluation of the sustainability of water use across the entire value chain, the formulation of water consumption and pollution reduction targets for both the company's operations and supply chain, the implementation of a plan to achieve these targets, and proper reporting of targets and achievements (Hoekstra, 2014a). In priority catchments, the pursuit of collective action and community engagement is required (Sarni, 2011). High-priority river basins are, for example, the Colorado and San Antonio basins in North America; the Lake Chad, Limpopo, and Orange basins in Africa; the basins of the Jordan, Tigris, Euphrates, Indus, Ganges, Krishna, Cauvery, Tarim, Yellow River and Yongding River in Asia; and the Murray–Darling basin in Australia (Hoekstra et al., 2012). For most companies, moving toward a sustainable supply chain is a much bigger challenge than greening their own operations, because the WF of the supply chain is often up to 100 times bigger than the company's operational footprint and can be influenced only indirectly. Common reduction targets in the beverage industry, such as going from 2 to 1.5 L of water use in the bottling plant per liter of beverage, have little effect on the larger-scale given that the supply chain WF of most beverages is approximately 100 L of water per liter of beverage or even more (Hoekstra, 2013).

The increasing interest in how companies relate to unsustainable water use calls for greater transparency on water consumption and pollution. Openness is required at different levels: the company, product, and facility level. Driven by environmental organizations and the investment community, businesses are increasingly urged to disclose relevant data at a company level regarding how they relate to water risks (Deloitte, 2013). Simultaneously, there is an increasing demand for product transparency through labeling or certification. Despite the plethora of existing product labels related to environmental sustainability, none of these includes criteria on sustainable water use. Finally, there is a movement to develop principles and certification schemes for sustainable site or facility management, such as the initiatives of the European Water Partnership and the Alliance for Water Stewardship. Despite progress in awareness, barely any companies in the world report on water consumption and pollution in their supply chain or reveal information about the sustainability of the WF of their products.

Much confusion exists regarding what needs to be measured and reported. Traditionally, companies have focused on monitoring gross water abstractions and compliance with legal standards. However, net water abstractions are more relevant than gross abstractions, and meeting wastewater quality standards is not enough to discard the contribution to water pollution made by a company. Regarding terminology and calculation standards, the Water Footprint Network—a global network of universities, nongovernmental organizations, companies, investors, and international organizations—developed the global WF standard (Hoekstra et al., 2011). The International Organization for Standardization developed a reporting standard based on LCA (ISO, 2014). Both standards emphasize the need to incorporate the temporal and spatial variability in WFs and the need to consider the WF in the context of local water scarcity and water productivity. In practice, companies face a huge challenge in tracing their supply chain. Apparel companies, for example, have generally little idea of where their cotton is grown or processed, yet the growing and processing of cotton are notorious water consumers and polluters. It is difficult to see quick progress in the field of supply chain reporting if governments do not force companies to do it.

The indirect blue and gray WF of many industries is often many times greater than their direct, operational WF. Nevertheless, most industries restrict their efforts to reducing their operational WF, leaving the supply chain WF out of scope. Studies performed by companies like Coca-Cola, PepsiCo, SABMiller, and Heineken have shown that the supply chain WF for beverage companies can easily be more than 99% of their total WF. Nevertheless, all these companies apply a "key performance indicator" for water that refers to the water use in their own operations only. Investments are geared to perform better in this respect, which means that, under the goal of sustainability, investments are made that aim to reduce that 1% of their total WF. It is difficult to imagine that these investments will be most cost-effective if sustainability is the actual goal. Incorporating sustainability principles into a company's business model would include the adoption of mechanisms to secure sustainable water use in the supply chain.

WFs per unit of product strongly vary across different production locations and production systems. Therefore, we need to establish WF benchmarks for water-intensive products such as food and beverages, cotton, cut flowers, and biofuels. The benchmark for a product will depend on the maximum reasonable water consumption in each step of the product's supply chain based on the best-available technology and practice. Benchmarks for the various water-using processes along the supply chain of a product can be taken together to formulate a WF benchmark for the final product. An end-product point of view is particularly relevant for the companies, retailers, and consumers who are not directly involved in the water-using processes in the early steps of the supply chains of the products they are manufacturing, selling, or consuming but are still interested in the water performance of the product over the chain as a whole. WF benchmarks will offer a reference for companies to work toward and a reference for governments in allocating WF permits to users. Manufacturers, retailers, and final consumers on the lower end of the supply chain get an instrument to compare the actual WF of a product with a certain reference level. Business associations within the different sectors of economy can develop their own regional or global WF benchmarks, although governments can take initiatives in this area as well, including the development of regulations or legislation. The latter will be most relevant to completely ban worst practices.

Companies should strive toward zero WF in industrial operations, which can be achieved through nullifying evaporation losses, full water recycling, and recapturing chemicals and heat from used water flows. The problem is not the fact that water is being used, but that it is not fully returned to the environment or not returned clean. The WF measures exactly that (the consumptive water use and the volume of water polluted). As the last steps toward zero WF may require more energy, it may be necessary to find a balance between reducing the water and the carbon footprint. Furthermore, companies should set reduction targets regarding the WF of their supply chain, particularly in areas of great water scarcity and in cases of low water productivity. In agriculture and mining, achieving a zero WF will generally be impossible, but in many cases the water consumption and pollution per unit of production can be reduced easily and substantially (Brauman et al., 2013).

When formulating WF reduction targets for processes in their operations or supply chain, companies should look not only at the numbers but also at the geographic locations where their WF is sited. Priority is to be given to WF reduction in catchments in which the overall footprint exceeds the carrying capacity or assimilation capacity of the catchment. It has been argued that reduction in water-abundant catchments does not make sense (Pfister and Hellweg, 2009), but this is based on a misunderstanding. Because the WF (m^3/product unit) is simply a reverse of water productivity (product units per m^3), it is difficult to see why one would not set targets regarding the reduction of the WF of a product, which is the same as setting targets regarding the increase of water productivity. The relevance of increased water productivities worldwide, also in water-abundant places, can be illustrated with the following example (Hoekstra, 2013). Suppose the hypothetical case of two river basins with the same surface (Table 7.6). Basin A is relatively dry and has, on an annual basis, 50 water units available. This is the maximum sustainable WF, which is, however, exceeded by a factor of two. Farmers in the basin consume 100 water units per year to produce 100 crop units.

Table 7.6 Example of How Overexploitation in a Water-Stressed River Basin (A) Can Be Solved by Increasing Water Productivity in a Water-Abundant Basin (B)

		Current Situation		Possible Solution	
Parameter	**Unit**	**Basin A**	**Basin B**	**Basin A**	**Basin B**
Max. sustainable WF	Water units/unit of time	50	250	50	250
WF	Water units/unit of time	100	200	50	200
Production	Product units/unit of time	100	100	50	200
WF per product unit	Water units/ product unit	1	2	1	1
Water productivity	Product units/ water unit	1	0.5	1	1

Source: From Hoekstra (2013).

Basin B has more water, 250 water units per year, available. Water is more abundant than in the first basin, but water is used less efficiently. Farmers in the basin consume 200 water units per year to produce 100 crop units, the same amount as in the first basin but using two times more water per crop unit. A geographic analysis shows that in basin B, the WF (200) remains below the maximum level (250), so this is sustainable. In basin A, however, the WF (100) by far exceeds the maximum sustainable level (50), so this is clearly unsustainable. The question is, should we categorize the crops originating from basin A as unsustainable and the crops from basin B as sustainable? From a geographic perspective, the answer is affirmative. In basin A, the WF of crop production needs to be reduced, and that seems to be the crux. However, from a product perspective, we observed that the WF per crop unit in basin B is two times larger than in basin A. If the farmers in basin B would use their water more productively and reach the same water productivity as in basin A, then they would produce twice as many crops without increasing the total WF in the basin. It may be that farmers in basin A cannot easily further increase their water productivity, so—if the aim is to keep global production at the same level—the only solution is to reduce the WF in basin A to a sustainable level by cutting production by half while enlarging production in basin B by increasing the water productivity. If basin B manages to achieve the same water productivity level as in basin A, then the two basins together could increase global production while halving the total WF in basin A and keeping it at the same level in basin B.

A final concern regarding good water stewardship is the extent to which a company pays for the full cost of its water use. Water use is subsidized in many countries, either through direct governmental investments in water supply infrastructure or indirectly by agricultural subsidies, promotion of crops for bioenergy, or fossil energy subsidies to pump water. Water scarcity and pollution remain unpriced (Hoekstra, 2013). To give the right price signal, users should pay for their pollution and consumptive water use, with a differentiated price in time and space based on water vulnerability and scarcity.

CONCLUSION

Spatial patterns of water depletion and contamination are closely tied to the structure of the global economy. As currently organized, the economic system lacks incentives that promote producers and consumers to move toward wise use of our limited freshwater resources. To achieve sustainable, efficient, and equitable water use worldwide, we need greater product transparency, international cooperation, WF ceilings per river basin, WF benchmarks for water-intensive commodities, water pricing schemes that reflect local water scarcity, and some agreement about equitable sharing of the limited available global water resources among different communities and nations.

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