The Water Footprint Concept and Water's Grand Environmental Challenges

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Widespread water scarcity, water pollution, and depletion of freshwater resources are among the grand environmental challenges of the 21st century related to water. Central to these challenges is the fact that humanity uses too much water. But what are we using all that water for? The water footprint concept can help answer this question, and more. Addressing the relation between human freshwater consumption and water's grand environmental challenges, the water footprint concept resonates with stakeholders within and beyond the walls of science. This Primer describes the basics of the water footprint concept, how it works, and why it came about. Drawing from recent studies in the new research field of Water Footprint Assessment, it highlights some intriguing applications and delves into what is next on the exciting interdisciplinary research agenda.

Grand Environmental Challenges Related to Water

Freshwater is a finite and vulnerable resource, essential to sustain life, development, and the environment. However, despite its readily acknowledged importance, the way humanity has managed—and continues to manage—its precious water resources has led to a number of grand environmental challenges related to water. Numerous river basins worldwide are facing water scarcity. Many water bodies are polluted with all sorts of substances, and stocks of both surface water and groundwater are depleted in many places around the world. As a consequence, ecosystems and soils have degraded, sometimes beyond repair. Species that depend on these water resources are losing their habitat and are going extinct at alarmingly high rates. Finally, vulnerability of water systems to (climate) shocks has increased dramatically.

The main drivers for the overuse and pollution of water in rivers, lakes, and groundwater bodies are population growth and economic development. More people means more consumption of goods and services that require water for their production, and wealthier people typically consume more goods and services per person. Specifically, when affluence rises, people tend to shift toward diets that contain more animal products. Omnivorous diets are generally more water intensive to produce than vegetarian diets. Climate change is also affecting the use of water resources, as warmer temperatures, erratic rainfall, and extreme weather events raise demand for water by farmers, industries, households, and power producers. While both science and policy discussions on these water challenges are often dominated by concerns over the role and impact of climate change, it is important to note that our current water crises are best explained by growing populations and consumption of water-intensive goods and services. Even if we manage to reduce or prevent additional negative effects of climate change from happening, humanity's unquenchable thirst for water will continue to rise and exceed environmentally sustainable thresholds.

The grand challenges around water transcend the environmental domain into the societal and economic realms. Competition over (access to) limitedly available water resources among various users has been linked to inequality and marginalized user groups, conflict—sometimes even violent conflict—and migration. If businesses and farmers cannot meet their demand for water to produce their goods or crops, deepening insecurity of food and energy is looming. The World Bank, among others, repeatedly warns of significant stalling of economic development because of shortages of (clean) freshwater, and the World Economic Forum lists water crises consistently as one of the largest global risks in terms of impact.

Although there is much more to say about the causes and consequences of these water crises, it is clear that humanity is using and polluting too much water for its various activities in many places around the world. This water use comes at the cost of nature and communities, and cannot be sustained into the future. Solving water's grand challenges thus calls for a considerable bridling of our water consumption. A question that naturally arises, then, is what are we using all that water for? This is where the water footprint concept comes in.

The Water Footprint Concept

At its base, the water footprint (WF) is a multidimensional indicator of volumetric water use and pollution. Whereas traditional water use indicators such as abstraction or withdrawals typically report (gross) volumes taken from a water body, the WF indicates (net) water consumption, which it explicitly links to a beneficiary human activity (e.g., growing a potato or washing a car). Consumption in WF terms refers to water that is "lost" from the system, and that therefore cannot be used for other purposes at that particular time at that particular location. In other words, a WF indicates water appropriation in both a time- and location-specific manner.

Next, the WF includes a connotation to the source of the water, as represented by its green, blue, and gray color components. The green WF refers to water from rainfall and melted snow that is stored in the root zone of the soil that evaporates back into the atmosphere. The green WF is particularly relevant for

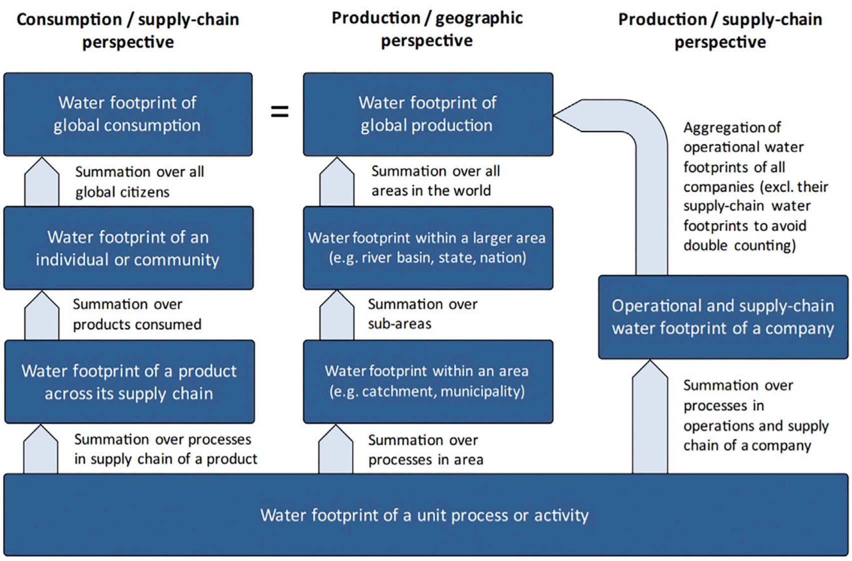

Figure 1. The Relation between Different Water Footprints
Water footprints of single processes or activities form the basic building blocks for the water footprint of a product, consumer, or producer or for the footprint within a certain geographical area. The footprint of global consumption is equal to the footprint of global production. Reproduced from Hoekstra (2017).

agricultural and forestry products because of the evaporation of water by plants and trees. The blue WF refers to water that has been sourced from surface water or groundwater that is either evaporated or incorporated into a product. Water consumed by irrigated agriculture, industry, and households is generally blue water. The gray WF refers to the amount of water that is needed to assimilate pollutants associated with a particular activity to meet local water-quality standards. A WF thus measures both the appropriation of freshwater as a natural resource (via the green and blue WF) and as an agent to assimilate waste (via the gray WF). In this way it unites water quantity and quality concerns in one indicator.

Finally, WFs are calculated at the base unit of a process or activity. These process WFs can be summed to a product, company, sector, or consumer level (Figure 1). In such aggregated representations, the WF considers both direct and indirect water use, meaning that it accounts for water consumed and polluted along each step of the value chain.

WF accounts have been investigated for a wide variety of processes, products, and sectors. Let me give a somewhat random yet telling anthology. We now know that it takes 1,200 L to produce a pizza Margherita (on average, summing water use over all ingredients of the pizza), 3,200 L for a pair of cotton jeans (summing water use and pollution from growing the cotton to dying and sewing the fabric), and 14,600 L for a gigajoule of energy generated by hydropower. The average person on Earth needs 3,800 L per day to support his or her lifestyle, most of which is indirect use needed to produce our food. A vegetarian diet is up to 40% less water intensive than that of an omnivore. Agriculture accounts for 92% of humanity's WF, while the remainder is roughly equally split between industry and household use. Of the nearly 10,000 billion cubic meters per year that humanity consumes across all sectors, 74% is green, 11% blue, and 15% gray water.

Insightful as these WF accounts are, from the onset the WF concept was designed to encompass more than "just" an indicator of water consumption. Both the multidimensional character described above and the broader framework shown in Figure 1 emerged for good reasons. First, there was the insight that water is not only a local but also a global resource. Through trade in products in international markets, water is virtually traded too. It is "embedded" in the product. Via trade, buyers or consumers of products in effect make use of water resources elsewhere. What is more, allocation of water resources by local authorities is increasingly driven by the dynamics of the global economy. Acknowledging this global dimension to water opened up a niche for studying water (footprints) in relation to trade and globalization.

Despite the global dimension to water, however, the impacts of water use and pollution remain largely local. Since local freshwater renewal rates are limited, the second important notion is that the volumetric WFs of human activities need to be studied in the context of local geographical boundaries or ecological limits. This contextualization of WFs in appropriate (local) settings helps answer the "so what?" question of a large or small volumetric WF. Comparing volumetric WFs with local water availability levels reveals the pressure placed by these WFs on local water systems. Doing so makes WF accounts more meaningful and actionable toward solving the grand challenges related to water.

The third driver that was instrumental in the development of the broader WF concept came from outside the walls of science. As multinational companies in particular learned about the concept, they wanted to assess their WF from a production perspective (recall Figure 1). This led to the intensive study of WFs across supply chains of products and—perhaps more importantly—to the development of the Global Water Footprint Assessment Standard (Hoekstra et al., 2011). In this widely adopted method, four clear steps help practitioners and academics alike to systematically: (1) scope their water footprint assessment; (2) make volumetric WF accounts; (3) place these accounts in their broader and local sustainability contexts; and (4) propose (policy-relevant) response options. Over the decade that passed since the publication of this standard, the WF concept has transformed into a new field of interdisciplinary scientific discourse called Water Footprint Assessment. The next section explores some recent applications that were undertaken in this budding field.

Applications of the WF Concept

Water Footprint Accounting

The first application of the WF concept is in answering the question I started with: what is humanity using its precious water resources for? This analysis, called WF accounting, is what

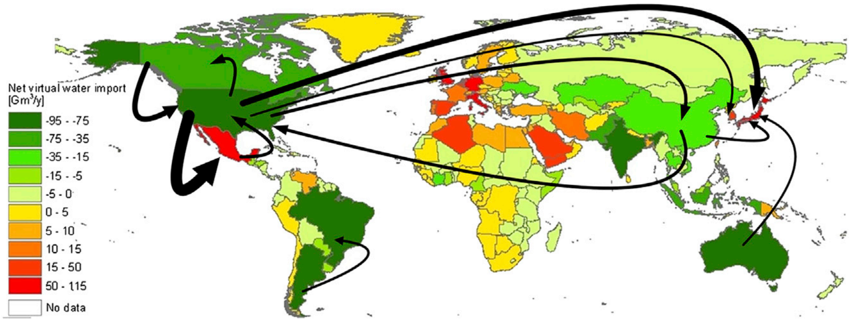

Figure 2. Virtual Water Balance per Country and Direction of Major Gross Virtual Water Flows Related to Trade in Agricultural and Industrial Products

In green-colored countries, the amount of water consumed to make products that are exported is larger than the amount needed to produce products that are imported, making them net virtual water importers. The opposite goes for yellow- and red-colored countries, which are net virtual water exporters. Reproduced from Hoekstra and Mekonnen (2012).

made the concept resonate with both the general public at large and a widening scientific community in particular. Many studies explored WFs of processes and commodities, ranging from local empirical case studies to high-resolution modeling at the global level. These studies showed how explicitly linking water use to human activities helps us understand the amounts of water that are being allocated—often implicitly—to the production of food, feed, fuel, and fibers. As the WF concept provides a systematic language to express units of water (cubic meters) in units of food (tons of produce) or units of energy (joules or calories), for example, it enables energy researchers designing carbon neural energy mixes to assess the water cost of that energy mix. Hydropower, it turned out, is associated with a large blue WF, and bioenergy has a large green WF that moreover may compete with food production.

The separate treatment of green and blue sourcing of water emphasized the importance of green water in food production. Green water is often taken for granted or overlooked in traditional agricultural water-management studies that typically deal with blue (irrigation) water only. At the same time, combining water quantity (green and blue WFs) and quality (gray WFs) concerns laid bare inevitable trade-offs between the two WF components. For example, in boosting crop yield by adding fertilizers the green-blue WF per unit of crop may be reduced, while at the same time the gray WF may increase because of the leaching out of excessive fertilizers to water bodies.

Spatial variations in WFs also facilitated analyses of efficient water use. Even for similar soils, climatic conditions, and farming practices, studies found major differences in the amount of water that is needed to produce a unit of crop from one place to the other. Reducing these inefficiencies has a substantial water-saving potential that can directly contribute toward solving water's grand challenges.

Water Footprint Sustainability Assessment

I explained earlier that in order to interpret volumetric WFs in a meaningful way, they have to be contextualized in an appropriate (local) setting. Comprising the sustainability assessment of a Water Footprint Assessment according to the Global Standard, local WFs can be compared with local sustainable water availability levels. From hydrological studies we learn how much water is available when and where; from ecologists we hear how much needs to be reserved for nature. What remains can then be sustainably appropriated by humans. If WFs exceed these maximum sustainable water availability levels, water scarcity results. Likewise, if more pollutants (e.g., fertilizers, pesticides, pharmaceuticals) are added to a water body than it can assimilate, water pollution results. Numerous local and global studies mapped periods and places where green, blue, or gray WFs exceed such local ecological thresholds. Worldwide, it is now estimated that over four billion people live in regions that face blue water scarcity at least one month of the year. Over half of the green water resources are overexploited, and most river basins worldwide are polluted by fertilizer leaching. Because the water consumption underlying such sustainability assessments is linked to processes and products, the WF concept is instrumental in identifying causes and contributions of specific human activities toward these detrimental water challenges. It informs producers, consumers, and policy makers alike where to effectively and practically target reduction efforts.

The Global Dimension of Water

Other applications of the WF concept are presented in studies that focus on the global dimension of water use. To calculate indirect WFs of products, consumers, and other aggregate WF levels (recall Figure 1), supply chains and trade flows have to be unearthed. Tracing these globally interwoven trade chains lays bare intriguing links between producers and consumers. Figure 2, for example, shows the major virtual water flows between countries as a result of trade in agricultural and industrial commodities. Green-colored countries export more water in virtual form than they import. Yellow and red countries, to the contrary, depend on foreign water resources to meet their needs. Such virtual water-flow analyses reveal interdependencies between regions and countries, again linked to (trade in) specific commodities. It illustrates how water has become a truly geopolitical resource.

Recognizing these global and political aspects, governments (particularly of dryer countries such as in the Middle East and North Africa) utilize these virtual water studies to explore their sometimes unavoidable dependency on (possibly unstable) trade partners for certain key commodities, and to inform their national food security strategies. Likewise for businesses, tracing their supply chains helps them understand risks related to water that could potentially harm their operations, as well as how these operations themselves might generate a negative impact on water systems.

The WF of consumption of individuals also has a clear global component. Various studies investigated how lifestyles and diets are supported by external water resources. For example, the typical Dutch consumer has externalized 95% of his or her WF to other countries, even though the Netherlands is a relatively water-rich country with a large potential to be more self-sufficient. What is more, a large part of this externalized WF of

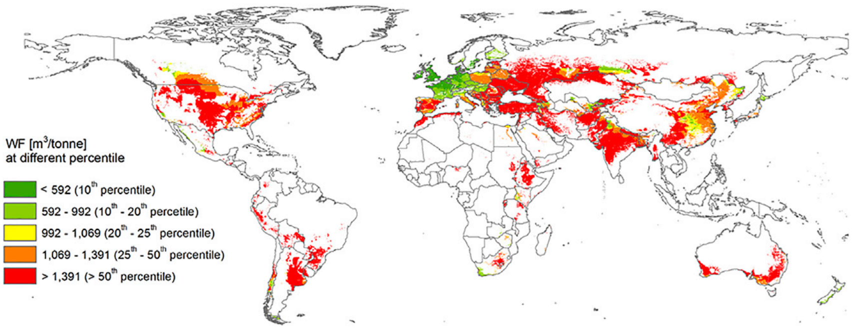

Figure 3. The Spatial Distribution of the Green-Blue Water Footprint of Wheat at Different Percentiles

If a water footprint benchmark is set at the 25th percentile of production and all producers would meet this benchmark, the worldwide water footprint of wheat could be reduced by 39%. Reproduced from Mekonnen and Hoekstra (2014).

consumption is unsustainable, as it was found that almost half of the externalized WF of Dutch consumption lies in regions that are already affected by water scarcity. Such analyses show how goods consumed by a person in one country can be traced back and linked to negative impacts on foreign water bodies where the product originates from.

Toward Policy Relevance

Several WF assessment studies proposed concrete policy recommendations to address water's grand challenges. First, setting WF caps per river basin is proposed as a promising measure to ensure that total water consumption for human activities in a particular basin stays within sustainable boundaries. Designed to achieve environmentally sustainable use of water, WF caps can help authorities to limit the amount of water permits they issue to the various demanding users without harming the environment.

Formulating WF benchmarks per water-using activity is another suggestion, aimed at achieving efficient water use. A WF benchmark is a reference level that indicates a reasonable amount of water use for a particular activity. If a producer uses more water than the WF benchmark, that producer is apparently wasting water needlessly (Figure 3). Adopting best practices may reduce WFs to the WF benchmark. In agriculture, this may imply changing from inundating the entire field to irrigate plants to much more efficient drip irrigation systems that provide just enough water directly to the plant roots. In industry, this means transitioning to closed-loop systems where all water is treated and reused within the factory's fence.

Combining the two recommendations, water managers may issue permits up and until the local WF cap, but only to those producers or activities that meet the WF benchmark for their proposed activity. Elements of these recommendations are now starting to find their way to actual policies, with Spain being the first country to incorporate WF assessments in drafting river basin plans.

Preliminary attempts have been made to propose fair WF shares for consumption in order to achieve more equitable and inclusive use of water. These efforts, however, require more research before practical policy recommendations can be made.

For a more comprehensive overview of applications of the WF concept, please see Hoekstra (2017).

Outlook and Opportunities

The number of studies using the WF concept in any of its many forms or applications is growing rapidly. Given the severity of the grand challenges related to water, research interest can also be expected to continue to grow. In the body of literature to date, most emphasis has been on the accounting of WFs and virtual water flows. As more detailed maps, time series, and other data are being developed for crops, industrial activity, pollutants, climate conditions, soil properties, farming practices, and trade statistics, WF accounts that use these as input will further improve. The same goes for sustainability assessments of WFs. Improved understanding and granularity of hydrological models, environmental flow methods, and global supply chains help better evaluate WFs in increasingly detailed contexts.

To date in current literature, formulating response options to reduce unsustainable WFs has been underemphasized. A large gap—and thus research opportunity—remains in understanding dynamics of proposed measures or policy recommendations that effectively reduce WFs. For example, if response options are tested in a specific location or during a particular time period, how transferrable are they to other settings? How are we to address local impacts if the drivers are global? What if a ''water'' solution is found in changing trade policy or energy policy, or even in changing people's habits and diets? Or on a more practical level, which role can stakeholders play—water managers and direct users such as households, farmers, and industries, but also indirect stakeholders such as consumers, policy makers, and investors?

The WF is a member of a broader family of resource footprints, including land, carbon, and material footprints. Future research may explore to what extent differing methodologies behind these environmental footprints can be synthesized or otherwise better aligned, for example to do trade-off analyses between various footprints or resources. This will help us to better understand when and where pursuing a smaller WF comes at the cost of a larger carbon footprint and vice versa, or whether perhaps the opposite is true and both water and carbon footprints can be reduced at the same time.

Additional lines of inquiry revolve around water-for-energy and water-for-food studies—for example, in the context of reaching the UN's Sustainable Development Goals on water, food, and energy. Potential research questions are: Is there enough water to support the energy transition toward carbon neutral energy mixes? What is the role of bioenergy and hydropower in these mixes? What are the water requirements of the diet of the future? What is the role of animal products in these diets given water constraints? What is the effect of intensive versus extensive agricultural management policies on the WF? What is the potential of smart, precision, or urban agriculture on the gray WF of food? Is there enough water to feed 10 billion people within Earth's planetary boundary on water use? Also under climate change? What comprises a fair WF of consumption, or (a right to) a minimum WF of consumption?

The above research questions illustrate the fundamental interdisciplinary and integrative nature of the field of Water Footprint Assessment. Their breadth and width underscore that the WF concept can be applied in many disciplines or subsets thereof, from nexus to environmental footprinting studies and from development to policy studies.

A Shared Responsibility

Reducing water scarcity, pollution, and depletion of freshwater resources is both urgent and a shared responsibility. The WF concept has been shown to resonate with key actors along the science-policy-action interface, informing academics, policy makers, business people, and consumers alike to better understand, frame, and respond to the looming water crises. The field of Water Footprint Assessment holds great potential for many more relevant and interdisciplinary studies to emerge. I therefore challenge you to see how this exciting concept can advance your future research toward solving water's grand challenges.

ACKNOWLEDGMENTS

Large parts of the content of this Primer are based on the substantive oeuvre of Prof. Dr. Arjen Hoekstra, who introduced the WF concept in 2002 and helped it mature ever since. On November 18, 2019, he suddenly and unexpectedly passed away much too soon. Arjen was a visionary who wanted to change the world through his scientific thinking. While many, including myself, are still grieving over this great loss of a colleague, mentor, and friend, I trust that his legacy will only grow with time because the topics it touches on are more relevant than ever. I dedicate this piece to him. This research was partially funded by the European Research Council under the European Union's Horizon 2020 Research and Innovation Programme (Earth@lternatives project grant agreement no. 834716).

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