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Human appropriation of natural capital: A comparison of ecological footprint and water footprint analysis

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ABSTRACT

The water footprint concept introduced in 2002 is an analogue of the ecological footprint concept originating from the 1990s. Whereas the ecological footprint (EF) denotes the bioproductive area (hectares) needed to sustain a population, the water footprint (WF) represents the freshwater volume (cubic metres per year) required. In elaborating the WF concept into a well-defined quantifiable indicator, a number of methodological issues have been addressed, with many similarities to the methodological concerns in EF analysis. The methodology followed in WF studies is in most cases analogous to the methodology taken in EF studies, but deviates at some points. Well-reasoned it has been chosen for instance to specifically take into account the source and production circumstances of products and assess the actual water use involved, thus not taking global averages. As a result one can exactly localise the spatial distribution of a water footprint of a country. With respect to the outcome of the footprint estimates, one can see both similarities and striking differences. Food consumption for instance contributes significantly to both the EF and the WF, but mobility (and associated energy use) is very important only for the EF. From a sustainability perspective, the WF of a country tells another story and thus at times will put particular development strategies in a different perspective. The paper reviews and compares the methodologies in EF and WF studies, compares nation's footprint estimates and suggests how the two concepts can be interpreted in relation to one another. The key conclusion is that the two concepts are to be regarded as complementary in the sustainability debate.

1. Introduction

In the early 1990s the concept of the ecological footprint (EF) was introduced, a measure of the human appropriation of the globe's biologically productive areas. About ten years later a similar concept was launched, the water footprint (WF), measuring the human appropriation of the globe's freshwater resources. Although both concepts have different roots and measuring methods differ in some respects, the two concepts have in common that they translate human consumption into natural resource use. The EF measures everything in use of space (hectares), whereas the WF measures the total use of freshwater resources (in cubic meters per year).

This paper provides a review of the background and methods of EF and WF analysis with a focus on a comparison of the two concepts and the calculations methods. With some examples it shows that measuring human consumption in terms of total use of space puts emphasis on other types of impacts and thus provides another story than measuring human consumption in terms of freshwater appropriation. It

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will be argued that both indicators can be used in a complementary way.

With respect to the methodology behind EF analysis the study most heavily draws upon Chambers et al. (2000), Monfreda et al. (2004) and Wackernagel et al. (2005). For estimates of national EFs we have used Hails et al. (2006). With respect to both the methodology of WF analysis and actual estimates of national WFs the study primarily uses Hoekstra and Chapagain (2007a, 2008).

2. Roots of EF and WF analysis

2.1. *Ecological footprint analysis*

The EF concept has been introduced in the 1990s by William Rees and Mathis Wackernagel (Rees, 1992, 1996; Rees and Wackernagel, 1994, 1996; Wackernagel and Rees, 1996, 1997). The concept is rooted in the search for indicators of sustainable development and more in particular the wish to measure how the human appropriation of the earth's resources relates to the carrying capacity of the earth. For that reason, the authors originally spoke about 'appropriated carrying capacity' instead of 'ecological footprint'. The aggregated use of land is seen as a good common denominator for expressing human's impact on the earth's natural resources.

The EF measures how much nature, expressed in the common unit of 'bioproductive space with world average productivity', is used exclusively for producing all the resources a given population consumes and absorbing the waste they produce, using prevailing technology (Chambers et al., 2000, p.31). An EF is generally expressed in hectares. EFs can be calculated for individuals as well as for any well-defined community, including villages, towns, cities, provinces, nations or the global population as a whole. In addition, EFs are calculated for organisations, particular human activities or specific goods or services.

The total EF of an individual or community breaks down into a number of components. Often six components are distinguished (Monfreda et al., 2004): use of arable land (for food, feed and other agricultural products), use of pasture land (for animal grazing), use of forest/woodland (for timber), use of built-up land (for living etc.), use of productive sea space (for fish), and use of forest land to absorb CO_2 that was emitted due to human activities. The first three categories are sometimes taken together as 'use of productive land'.

The EF deviates from other sustainability indicators in two respects: it expresses the impacts of humanity on the environment in one common unit (use of bioproductive space) and it can be related to the carrying capacity of the earth (the available bioproductive space or so-called 'biocapacity'). Particularly the latter has been regarded by the authors of the EF concept as the greatest step forward (Chambers et al., 2000, p.29).

2.2. *Water footprint analysis*

The WF concept has been introduced in 2002 by the author at the International Expert Meeting on Virtual Water Trade, which was held in Delft, the Netherlands (Hoekstra, 2003). Water footprints of nations were quantitatively assessed by Hoekstra and Hung (2002) and more comprehensively by Hoekstra and Chapagain (2007a, 2008). Although the term 'water footprint' has obviously been chosen by the author in analogy to the ecological footprint and although the potential to bring the two concepts together in one analytical framework has been recognised from the beginning, the WF concept has other roots than the EF concept.

The WF concept is primarily rooted in the search to illustrate the hidden links between human consumption and water use and between global trade and water resources management. The starting point for the author's research was the discontent with the fact that water resources management is generally seen as a local issue or a river basin issue at most. The global dimension of water resources management has been overseen by most of the water science and policy community (Hoekstra, 2006). In addition, the production (supply) perspective in water resources management is so dominant that it is hardly recognised that water use relates in the end to human consumption. The WF concept has primarily been introduced in the water science community in order to demonstrate that both a consumer dimension and a global dimension should be added in considerations of good water governance. The WF concept has thus far primarily been discussed at water science and policy forums, not at environmental science forums. After the launch at the expert meeting in Delft in 2002 the concept has subsequently been discussed at various international water meetings, such as the 3rd World Water Forum in Japan in 2003, the e-conference on 'Virtual Water Trade and Geopolitics' organised by the World Water Council in 2003 (WWC, 2004), the expert meeting on 'Virtual Water Trade organised by the German Development Institute in Bonn in 2005 (Horlemann and Neubert, 2007), the 4th World Water Forum in Mexico City in 2006, the expert meeting on 'Global Water Governance' organised by the Global Water System Project in Bonn, 2006, and the expert meeting on 'Virtual Water Trade' organised by the Institute for Social–Ecological Research in Frankfurt in 2006 (Hummel et al., 2007).

The WF of an individual or community is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community (Hoekstra and Chapagain, 2008). A WF can be calculated for any well-defined group of consumers, including a family, village, city, province, state or nation (Ma et al., 2006; Hoekstra and Chapagain, 2007b; Kampman et al., 2008). A WF can also be calculated for a specific activity, good or service. For example, Chapagain et al. (2006b) elaborate on the water footprint of cotton; Chapagain and Hoekstra (2007) assess the water footprint of coffee and tea; and Gerbens-Leenes et al. (2008) estimate the water footprint of primary energy carriers. The water footprint can also be applied to a business or organisation (WBCSD, 2006; Gerbens-Leenes and Hoekstra, 2008). A WF is generally expressed in terms of the volume of freshwater use per year. The focus on *fresh* water is important because fresh water is scarce, not water in general. The volume of fresh water on earth is only 2.5% of the total amount of water on earth (Gleick, 1993).

The idea of the water footprint builds on the concept of 'embedded water' or 'virtual water' that was earlier introduced by Allan (1998) when he studied the possibility of importing

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virtual water (as opposed to real water) as a partial solution to problems of water scarcity in the Middle East. Allan elaborated the idea of using virtual-water import (coming along with food imports) as a tool to release the pressure on the scarcely available domestic water resources. Virtual-water import thus becomes an alternative water source, alongside endogenous water sources. Imported virtual water has therefore also been called 'exogenous water' (Haddadin, 2003). In fact, the concept is similar to concepts like embodied energy, land or labour, so that one could also speak about 'embodied water' (Chambers et al., 2000, p.96). The interest in virtual water started to grow rapidly once the first quantitative studies were published (Hoekstra and Hung, 2002; Hoekstra, 2003; Chapagain and Hoekstra, 2004; Oki and Kanae, 2004; De Fraiture et al., 2004). Hoekstra and Chapagain (2008) define the 'virtual-water content' of a product (a commodity, good or service) as the volume of freshwater used to produce the product. It refers to the sum of the water use in the various steps of the production chain. The adjective 'virtual' refers to the fact that most of the water used to produce a product is not contained in the product. The real-water content of products is generally negligible if compared to the virtual-water content. 'Virtual-water trade' occurs when water-intensive products are traded from one place to another (Hoekstra and Hung, 2005; Chapagain and Hoekstra, 2008).

The WF of an individual or community can be estimated by multiplying all goods and services consumed by their respective virtual-water content. The WF of a nation consists of an internal and an external part. The internal WF refers to the appropriation for own consumption of water resources within the country, while the external WF refers to the appropriation of water resources in other countries.

The total WF of an individual or community breaks down into three components: the blue, green and grey WF. The blue WF is the volume of freshwater that evaporated from the global blue water resources (surface water and ground water) to produce the goods and services consumed by the individual or community. It excludes the part of the water withdrawn from the ground or surface water system that returns to that system directly after use or through leakage before it was used. The green WF is the volume of water evaporated from the global green water resources (rainwater stored in the soil). The grey WF is the volume of polluted water that associates with the production of all goods and services for the individual or community.

From the beginning, water footprints have been defined based on the actual water use per unit of consumption, not on the basis of the average global water use per unit of consumption. This means that water footprints can only be calculated by analysing the source of consumer goods and consider the actual water use in the countries of origin (where production takes place).

The WF deviates from other water use indicators in three respects: it measures underlying water appropriation of goods and services by integrating water use and pollution over the complete production chain, it visualises the link between (local) consumption and (global) appropriation of water resources, and it measures not only blue water use (as previously existing indicators) but also green water use and the production of polluted grey water.

3. Comparison of EF and WF analysis from a methodological point of view

There is a clear parallel between EF and WF analysis as shown in Table 1. The next sections will compare both types of analysis by addressing one-by-one a few methodological issues.

3.1. *Calculating a footprint: the item-by-item and the balance-based approach*

In EF analysis two alternative calculation methods can be used: the so-called component-based calculation and the compound calculation (Simmons et al., 2000; Chambers et al., 2000 p.67–69; Wackernagel et al., 2005, p.5). In a component-based calculation, one starts with identifying all the individual items—goods and services—and amounts thereof, that a given population consumes. In a second step one multiplies, for each item, the consumption volume by the associated land requirement per unit of consumption. The total EF consists of the sum of the calculated EF-components (where the separate components are usually weighted, see Section 3.4). In a compound calculation, one does not build up the total EF through an item-by-item approach, but starts from the overall consumption balance. First, the consumption within a nation is calculated as the national production plus imports minus exports. Consumption data are then translated into appropriated bioproductive area by using conversion rates (where the rates are usually global averages, see Section 3.5). The analysis is carried out separately for a number of consumption categories, each of which relates to a specific land use type. A commonly used list of land use types is the list mentioned in Section 2.1. The total EF is again obtained by an addition of the (usually weighted) areas per land use type.

In WF analysis there have also been proposed two calculation methods, which show a parallel with the two methods applied in EF analysis. In WF analysis, the two approaches have been called the bottom-up and the top-down approach (Hoekstra and Chapagain, 2008). The bottom-up approach is an item-by-item approach, resembling the EF component-based approach. In this approach the WF is found by multiplying all goods and services consumed by the inhabitants of a country by the respective water needs for those goods and services. The top-down approach is balance-based and resembles the EF compound calculation method. In this approach, the WF of a nation is calculated as the total use of water resources within the country plus the gross virtual-water import minus the gross virtual-water export. Virtual-water import refers to the volume of water used in other countries to make goods and services imported to and consumed within the country considered. Virtual-water export refers to the volume of water used domestically for making export products, which are consumed elsewhere.

The balance-based (compound, top-down) calculation method is considered most practical for a rapid assessment of footprints of nations. This conclusion has independently arrived at by EF researchers (Chambers et al., 2000; Monfreda et al., 2004; Wackernagel et al., 2005) and WF researchers (Hoekstra and Chapagain, 2008). The item-by-item (component-

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Table 1 – A comparison between EF and WF analysis

		EF analysis	WF analysis
Indicator of human appropriation of natural capital		Ecological footprint (EF)	Water footprint (WF)
Common denominator		Use of bioproductive space (in ha)	Use of freshwater resources (in m^3/yr)
Calculation methods	Item-by-item calculation method	Component-based calculation method	Bottom-up calculation method
	Balance-based calculation method	Compound calculation method	Top-down calculation method
Footprint components	Use of natural capital as a source	Use of arable land, use of pasture land, use of forest and woodland, use of built-up land, use of productive sea space	Use of green water (green WF), use of blue water (blue WF)
	Use of natural capital as a sink	Energy (CO_2 absorption) land	Use of water to assimilate pollution (grey WF)
Adding different footprint components		Actual areas are (in most EF-studies) weighted by equivalence factors before adding	Actual water volumes are added without weighting
Local versus global productivity		Most EF analyses are based on global average productivities (annual kg per global hectare)	A distinction is made between actual (local) and global average virtual-water content of a product (m^3/unit of product); WF analyses are based on actual virtual-water contents
Geographical specification		Using global hectares, the exact origin of the hectares are not specified	The WF is a geographically explicit indicator, not only showing volumes of water use and pollution, but also the locations
Ceiling to sustained natural resource appropriation		Sum of biologically productive areas (biocapacity) (in ha)	Available freshwater resources (in m^3/yr)
Ecological reservation		Biodiversity land	Environmental flow requirements

based, bottom-up) approach can be used for estimating a national footprint as well, but is considered more suitable for the assessment of the footprint of an individual, business or sub-national community where import-export data are not available.

The advantage of the item-by-item approach is that it is rather flexible, in the sense that one can choose the level of detail of analysis and adjust the items accounted for on the basis of the consumption characteristics of the community, entity or activity under consideration. Another advantage is that this approach, by its breakdown of impacts by activity, is easier to communicate and more instructive (Chambers et al., 2000, p.69). Calculation schemes based on the item-by-item approach can be translated into simple educational or awareness raising tools. Simple calculators for estimating a person's individual ecological footprint have been developed for example by Best Foot Forward,[1] the Global Footprint Network[2] and Redefining Progress.[3] A simple web-based water footprint calculator for assessing a personal water footprint has been developed by UNESCO-IHE in cooperation with the University of Twente.[4]

For estimating footprints of nations, it has been argued that the item-by-item approach has two disadvantages: it is more data-intensive and vulnerable to data variability and reliability (Chambers et al., 2000, p. 69; Hoekstra and Chapagain, 2008). The merit of the balance-based calculation is its easy replicability on the basis of publicly available global databases. Besides, the balance-based method is most effective in capturing indirect effects, because it captures the resources that are used up by the inhabitants of a country independent of the activity they are used for (Chambers et al., 2000, p. 73). On the other hand, in a recent study of the water footprint of the Netherlands, Van Oel et al. (2008) show that the item-by-item approach can be preferred under some specific circumstances. The item-by-item and balance-based calculations of a national footprint for a particular year theoretically result in the same figure only when there is no product stock change over a year. The balance-based calculation can theoretically give a slightly higher (lower) figure if the stocks of products increase (decrease) over the year. In addition, more importantly in practice, when the import and export of a country are large relative to its domestic production, which is typical for small trade nations, the balance-based approach can be very vulnerable to relatively small errors in the trade data. In such a case, the item-by-item approach will yield a more reliable estimate than the balance-based approach. In countries where trade is relatively small compared to domestic production, the reliability of the outcomes of both approaches will depend on the relative quality of the databases used for each approach. The item-by-item approach depends on the quality of consumption data, while the balance-based approach relies on the quality of trade data.

3.2. *Accounting for both sources and sinks*

In EF analysis, it is common to account not only for the bioproductive areas being used as a resource (e.g. for living or obtaining food or timber) but also for the bioproductive areas that are needed as a sink for human pollution. Most EF

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[1] Online available at: www.ecologicalfootprint.com and www.bestfootforward.com/footprintlife.htm.

[2] Online available at: http://ecofoot.org and www.footprintnetwork.org.

[3] Online available at: www.myfootprint.org.

[4] Online available at: www.waterfootprint.org.

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analyses quantify a component that is called the 'energy footprint' (in hectares), which refers to the area of forest that is necessary to compensate for human-induced CO_2 emissions (Chambers et al., 2000, p.67; Ferng, 2002).

In WF analysis a similar approach has been chosen. The total WF of an individual or community breaks down into three components: the blue, green and grey WF (Hoekstra and Chapagain, 2008). The first two refer to resource use, while the latter refers to the water volume required to assimilate pollution. The grey WF is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards (Chapagain et al., 2006b).

The rationale for including the energy footprint in the total EF and the grey water footprint in the total WF is similar: land and water do not function as resource bases only, but as systems for waste assimilation as well.

The approach to account in EF analysis for forestland needed to assimilate human-induced CO_2 emissions has been criticised with the argument that CO_2 assimilation by forests is one of the many options to compensate for CO_2 emissions, a very land-intensive option (Van den Bergh and Verbruggen, 1999). Similarly, one could argue that dilution is only one way of assimilating chemicals emitted into water bodies. An alternative would be wastewater treatment before disposal and reuse of the chemicals retrieved. This has been recognised and therefore the dilution volume is calculated based on the actual volume of chemicals disposed in natural water bodies, not on the volume of chemicals in the initial waste flow. As a result, an increase in wastewater treatment will indeed reduce the grey WF.

Another critique on the inclusion of the land component for CO_2 absorption is that the simple linear translation of CO_2 emissions into required areas of forestland is too simplistic and that the conversion factor used has a high degree of subjectivity (Van den Bergh and Verbruggen, 1999). Similar criticism could be formulated with respect to the grey WF. Indeed, the translation of human-induced pollutant flows into the environment into required dilution volumes for assimilation is based on water quality standards that bear a dimension of subjectivity. The view of the author is that including natural resource use for waste assimilation is consistent with the aim of being comprehensive in assessing total human appropriation of natural resources. But it should be recognised that this component of footprinting suffers more from knowledge weaknesses and subjectivity than the active resource-use component. But by making the conversion factors (ha/ton CO_2) and water quality standards (mg/l) explicit, the approach is verifiable and can be adjusted when improved insights allow.

3.3. *Preventing double counting*

One of the concerns in EF analysis has been the risk of double counting. Van den Bergh and Verbruggen (1999) for example claim that neglecting multi-functional land use will bias the calculated EF upwards. According to Chambers et al. (2000), however, care can be taken to avoid double counting. Besides, they argue that rather than double-counting a problem can be the underestimation of an EF due to neglecting the effects of various forms of contamination (other than CO_2) on bioproductive space.

In WF analysis double counting is prevented by dividing used water volumes over the various products obtained. For example, when a primary crop is processed into two different products or more (e.g. soybean processed into soybean flour and soybean oil), the virtual-water content of the primary crop is distributed over its separate products. This is done proportionally to the value of the crop products. It could also be done proportionally to the weight of the products, but this would be less meaningful (Hoekstra and Chapagain, 2008). In the case of calculating the grey WF, the dilution volumes associated with different types of pollutants are not simply added. Instead, it is identified which of the pollutants in a certain waste flow requires most dilution water; this pollutant is then taken as the most critical one, which means that if this pollutant has been sufficiently diluted, all the other pollutants have been sufficiently diluted as well (Chapagain et al., 2006b). This ignores possible cumulative effects of pollutants, so that the obtained grey WF estimate is conservative rather than an overestimate.

3.4. *Adding different footprint components*

In EF analysis, the aggregation of different footprint components into one aggregated EF has been a bit of a controversial subject (see e.g. Van den Bergh and Verbruggen, 1999, p.63; Van Kooten and Bulte, 2000). The three options that have been considered are: (1) simply adding the different types of land use without weighting, (2) adding the different areas with weighting based on the relative productivity of the different land types, and (3) not adding but presenting the different components separately. The first approach is simple but does not do justice to the fact that different types of land vary in terms of biological productivity (the rate of biomass production through photosynthesis). In other words, the 'value' of different land types for supporting humanity varies as a function of their biological productivity, the reason to use the relative productivity of land as a weight factor. The second approach is the one that has become most common in EF analysis (Wackernagel et al., 1999, 2002; Monfreda et al., 2004). In this approach, different types of land are brought into one comparable unit by multiplying land areas by a so-called equivalence factor, which is defined as the productivity of a certain land type divided by the average productivity of total bioproductive land. The resulting EF is then expressed in a sort of 'weighted', 'adjusted' or 'equivalent hectares', in most studies called 'global hectares' (as opposed to actual hectares). Van den Bergh and Verbruggen (1999) have suggested that land areas could possibly better be weighted on the basis of social rather than physically based weights, e.g. on the basis of their relative economic scarcity, but this proposal has received no follow-up. A third approach is not to add different EF components at all, with the argument that they are fundamentally different and that useful information gets lost when adding the components. This approach was for example chosen by Van Vuuren and Smeets (2000) in response to the criticism that had been formulated against the aggregation of the separate footprint components. In the view of the author of the current paper, however, the three approaches mentioned are not worth fundamental controversy because in

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reality they can easily be combined in one analysis, which is also done in practice: first one estimates and presents the actual, unadjusted areas per land use type (third approach), after which one can add them in two different ways and present both aggregates (first and second approach).

In WF analysis different types of water use are added without weighting, thus following the first approach as mentioned above. However, it has been recognised that for the purpose of policy formulation it is essential to explicitly distinguish and present the various WF components, which comes down to the third approach as mentioned above. An example of a study where the three WF components (green, blue, grey) are explicitly shown is the cotton footprint study by Chapagain et al. (2006b). It has been recognised that the three WF components have different characteristics, so that simply adding them makes that some relevant information gets lost. The main difference between green and blue water is that they are different in their scope of application. Green water can be productively used only for crop production and natural biomass production (support of ecosystem functioning), while blue water can be used for irrigating crops but also for various other types of domestic, agricultural and industrial water use. It has been said that the opportunity cost of blue water is generally higher than for green water (Chapagain et al. 2006a). From this perspective it can be argued to count 1 m^3 of blue water use more than 1 m^3 of green water use, but this idea has not been elaborated. Rather, it has been chosen to specify both the blue and green WF and compare each of them separately with the available blue and green water resources respectively.

Both EF and WF suffer from the critique that no distinction is made between 'sustainable' and 'unsustainable' resource appropriation. As Van den Bergh and Verbruggen (1999) formulate in their critique on EF analysis, it assumes that hectares used can simply be added, irrespective whether it concerns 'sustainable land use' or 'unsustainable land use'. They argue that extensive agriculture requires more land per unit of production than intensive agriculture, but the risk of land degradation in the case of the latter is larger than in the case of the former. Similarly, in WF analysis, appropriated water volumes are added without making a distinction between 'sustainable' and 'unsustainable' water use. In one case a certain volume of water use may have little effect on the local ecosystem, while in another case the same volume of water use can be far beyond a critical point. Although the observations made are correct, it does not subtract from the value of EF and WF analysis when perceived from the intended purpose. EFs and WFs are calculated to evaluate total appropriation of bioproductive space and freshwater resources in the context of the total available space and resources. Speaking in terms of 'sustainable' and 'unsustainable' use of land or water, as done above, presumes that one can attribute the sustainability or non-sustainability label to certain specific activities without looking at the total picture. EF and WF analysis aim to provide an overall picture.

3.5. *Using local or global average productivities*

Footprint studies can be carried out with either local or global average data on resource productivities. Most EF studies are based on global average parameters on land requirement per unit of good or service consumed and do not distinguish the exact origin of the products (Monfreda et al., 2004; Wackernagel et al., 2005). Existing WF studies, on the contrary, consider the origin of the goods and services and look at the actual water use at the place of production (Hoekstra and Chapagain, 2007a, 2008). Obviously, at the global level it does not matter whether EF or WF analysis is carried out on the basis of local or global average productivities, because adding the results obtained with local data will yield the same result as an analysis based on global average data. For a global analysis, working with global productivities therefore suffices.

Footprint calculations with local productivities demand much more data than computations with global average productivities. When estimating the footprint of a nation with the balance-based approach with local productivities, it is not enough to have specific productivity figures for the country itself. Trade data need to be specified now by trade partner and for each product productivities need to be known by trade partner. When computing a footprint using the item-by-item approach, consumption needs to be specified not only by item, but by origin as well.

Although EF analysis as it was originally introduced (Wackernagel and Rees, 1996; Wackernagel et al., 1997, 1999, 2002) and as it has become mainstream (Hails et al., 2006) is based on taking global average productivities, it does not mean that this approach is fundamental to EF analysis. In fact, it has been shown by various authors that EF analysis can be carried out based on actual, local productivities as well. Van Vuuren and Smeets (2000), for example, used local productivities when estimating the EFs of Benin, Bhutan, Costa Rica and the Netherlands. In order to do so they had to consider the origin of the products being consumed in the four countries. The land use behind imported products was estimated based on the productivities as in the regions of origin. When the import region was unknown, global average productivities were used for these imports. Gerbens-Leenes et al. (2002) used actual, local productivities in their assessment of the EF of the Netherlands, Lenzen and Murray (2001) did similarly for Australia, Haberl et al. (2001) and Erb (2004) for Austria, and Luck et al. (2001) for the twenty largest metropolitan areas in the USA. It is noted here that some of the studies that work with local productivities still work with global average productivities if it comes to converting consumption of imported products into land requirements (e.g. Van Vuuren and Bouwman, 2005).

Haberl et al. (2001) and Wackernagel et al. (2004a) carried out comparative studies in which they compared the outcomes of the 'conventional' approach (global averages) to the 'actual land area' approach. Wackernagel et al. (2004b) conclude that the two approaches can be applied to address different research questions. The method using global productivities can be used to answer the question of how much of the globally available bioproductive space is used by a given population. The method using local productivities can be used to address the question of how much actual area is used by a population. In EF studies, the choice to work with global average productivities is generally combined with the choice of weighting different land use types by equivalence factors (following the 'footprint standards' as in Wackernagel et al.,

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2005). The more unusual choice to work with local productivities is most of the time combined with the approach of not-adding or unadjusted adding different land use types (Van Vuuren and Smeets, 2000; Gerbens-Leenes et al., 2002).

In WF analysis the dominant approach is to work with local productivities. This choice has been driven by the research questions addressed by the various authors in the field of 'water footprint' and 'virtual water trade' analysis. An important question all the time is where and how nations or the global society as a whole can save water (Hoekstra, 2003; Oki and Kanae, 2004; De Fraiture et al. 2004; Wichelns, 2004; Hoekstra and Hung, 2005; Chapagain et al., 2006a). For that reason it has been considered key to look at local productivities, because only local data on productivities can tell where water use per unit of product is relatively large and where small. The water need per unit of product depends on both climate and water-use efficiency. Reducing water footprints through adjusting consumption patterns is one option, but reducing water footprints by producing where the climate is most suitable and by using water more efficiently are two other important options to be considered (Hoekstra and Chapagain, 2007a, 2008). When water footprints were calculated based on global averages, the production circumstances (climate and water-use efficiency) would not be a variable in the equation anymore.

The implication of the two different approaches—accounting for either global or actual local productivities—can be illustrated with the help of the equation proposed by Ehrlich and Holdren (1971): $I = P \times A \times T$, in which I stands for the impact of humanity on the environment, P for population (measured in terms of its size), A for affluence (expressed as consumption per capita) and T for technology (expressed in terms of environmental impact per unit of consumption). Both EF and WF are measures of I, with the only difference that EF takes the use of bioproductive space as the common denominator of environmental impacts of consumption and WF the use of freshwater resources. By using global average productivities in EF analysis, the factor T is taken as a (global average) constant. In WF analysis, the factor T is left as a variable. The result is that variations within EF-per capita estimates can be fully attributed to differences in consumption (A), whereas variations within WF-per capita estimates can be due to differences in consumption (A) but also to differences in the environmental impact per unit of consumption (T). It is noted here that T covers impact differences in its widest sense, so it does include differences in impacts due to the use of different technologies, but it also accounts for differences in impacts due to differences in production circumstances such as climate. I explicitly mention this here because water use in agriculture depends on both natural climate factors and agricultural practice. The factors are together responsible for yield differences between various locations.

The advantage of applying local productivities is that the calculated footprints more accurately reflect the actual impact of a particular consumption pattern. Both in terms of land and freshwater appropriation it makes a difference when and where for example the vegetables being consumed were produced. Using local productivities shows that footprints can be reduced by changing consumption volume and pattern but also by reducing the impact per unit of consumption through e.g. improved technology or production circumstances. The disadvantage of using actual, local productivities is that it requires more data and is more labour intensive. Besides, it is difficult to distinguish in the resulting footprint estimates the separate effects of consumption and production circumstances.

3.6. *Making explicit the geographic spreading of footprints*

Standard EF analysis is based on global average productivities and thus does not require making explicit from where consumer goods originate. WF analysis on the contrary has from the beginning of the idea been based on local productivities, which requires tracking down the origin of the consumer goods and the actual productivities at the place of production (Hoekstra and Hung, 2002). An underlying aim of WF analysis has been to uncover the hidden links between consumption in one place and water demand in another (Hoekstra and Chapagain, 2007a, 2008). This could open up the minds of water managers that traditionally see water as a local resource or a river basin resource at most (Hoekstra, 2006). In WF analysis an emphasis has been put also on distinguishing between an internal and an external water footprint of a nation. The issue of externalising a national WF is a relevant issue in two respects. First, water-scarce countries can externalise their WF in order to save their domestic water resources (some countries in the Middle East do so). Here, externalising a WF can be regarded as a positive thing. Second, however, externalising a national footprint also means shifting the environmental burden to a distant location. Here, externalising a WF gets a negative connotation. So, whether good or bad, the issue of internal versus external WF is considered key in addressing important water policy questions at both national and global level.

Also in EF analysis the idea of making footprints spatially explicit has been explored. Erb (2004) for example shows how the EF of Austria refers to land appropriation on each continent of the world. Luck et al. (2001) carried out a spatially explicit analysis of land appropriation of major metropolitan areas in the USA.

3.7. *Measuring natural capital availability*

A global footprint represents the total human appropriation of natural capital. The global EF refers to the human appropriation of the available bioproductive space and the global WF indicates the human appropriation of the available freshwater resources on earth. In both cases it is useful to see the actual appropriation in the context of the available capital. In the case of EF analysis, the available capital is called the 'total available biologically productive area' or 'biocapacity' in short (Chambers et al., 2000, p.177). Biocapacity at global level is estimated by adding up all bioproductive areas in the world weighted based on their relative productivity (using the earlier mentioned equivalence factors). To establish biocapacity at national level, different qualities of land are summed up while applying both yield factors and equivalence factors as weight factors for the different land qualities. A yield factor is the local productivity divided by the global average productivity.

In WF analysis, the available capital is called the 'annual freshwater availability', which consist of two components:

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green water availability and blue water availability. The green water availability is equal to the total evapotranspiration above land (minus human-induced evapotranspiration of blue water in order to prevent overestimation). The blue water availability is equal to actual runoff from land to oceans (plus human-induced evapotranspiration of blue water to correct for runoff that was already consumed before running into the ocean). The total annual freshwater availability, the sum of green and blue water availability, is equal to total precipitation above land.

3.8. *Fraction of natural capital to be reserved for biodiversity and ecosystem functioning*

Before comparing the global EF with the earth's biocapacity, it has been argued that the total biocapacity should first be lessened with a fraction to be reserved as 'biodiversity land', that is land for sustaining the globe's biodiversity. In this view, global biocapacity is not fully available for human appropriation, since part of it has to be reserved for biodiversity protection (Chambers et al., 2000, p.65). A question is then which fraction of the global biocapacity is required for that. Estimates range widely, from 12% (WCED, 1987) to 75% (Noss and Cooperrider, 1994). It can be argued that part of the EF, particularly the use of forest land, can count as biodiversity land, which has been a reason for many authors not to include the need for biodiversity land in their analysis.

Also in WF analysis it has been recognised that part of the freshwater availability has to be reserved for natural purposes (Hoekstra and Chapagain, 2008). Part of the green-water availability (evapotranspiration) is to be used for natural biomass production. Part of the blue-water availability (runoff) is to be set aside to fulfil environmental flow requirements (Smakhtin, 2001). According to Smakhtin et al. (2004), at least 30% of the world's river flows have to be allocated to maintain a fair condition of freshwater ecosystems worldwide. This is just the world average, river basin estimates range between 20 and 50%. Knowledge in this area is still poor. The ecological processes are often poorly understood, it is not clear what ecological standards have to be taken (when changes in the ecosystem become unacceptable), and next to minimum flow requirements one should also look at flow extremes, seasonal variations and variations over the years.

3.9. *Scale of analysis*

EF and WF analysis have in common that they can be applied at various spatial scales, ranging from the individual or household scale, through the village, town or city scale up to provincial, national, continental and global scale (Chambers et al., 2000, p.32; Hoekstra and Chapagain, 2008). Cross-scale comparisons are possible by expressing footprints in per capita units. In addition, EF and WF analysis can be carried out for particular organisations, activities or products. The footprints of different companies within one economic sector can be compared by expressing the footprints for example per unit of production volume or turnover. The footprints of various products can be compared by expressing the footprints for example per kilogram of product or per caloric value in case of food.

3.10. *Historical time series and scenarios for EF or WF*

Both EF and WF analysis use actual technological practice when taking data on productivities (Monfreda et al., 2004; Hoekstra and Chapagain, 2008). When estimating historical footprints, it has been shown that one can work with either variable productivities, as they were at the time, or with a fixed productivity at a reference point in time (Haberl et al., 2001; Wackernagel et al., 2004b). Obviously, the results show different things and have to be interpreted in different ways. Also when developing scenarios for the future footprints of nations or regions one will have to make assumptions about the productivities to be taken over the course of time (see e.g. Senbel et al., 2003; Van Vuuren and Bouwman, 2005).

4. Comparison of EF and WF estimates

4.1. *Global EF and WF*

According to the estimate by Hails et al. (2006) the global EF in 2003 was 14.1 billion global hectares. More than half (52%) of the global EF consists of the use of forestland for offsetting human-induced CO_2 emissions (including the offset of the CO_2-equivalent of nuclear energy). The second-largest component in the global EF is the use of arable land (21%), followed by the use of forest for timber (10%), use of fishing grounds (7%), use of pastureland for animal grazing (6%), and use of built-up land (4%).

The global WF is 7450 billion m^3/yr, an average for the period 1997–2001. Humanity's green WF is 5330 billion m^3/yr, while the combined blue-grey WF amounts to 2120 billion m^3/yr (Hoekstra and Chapagain, 2007a, 2008). The green WF fully refers to agricultural products. The combined blue-grey WF refers to agricultural products (50%), industrial products (34%) and domestic water services (16%). The size of the global WF is largely determined by the consumption of food and other agricultural products. The provided figures can be regarded as conservative estimates. Postel et al. (1996) for example estimate that the human appropriation of green water amounts to 18,200 billion m^3/yr, but this also includes green water appropriation in forestland used for human purposes. Their definition of human appropriation of freshwater is much broader than the one used in WF analysis. Further, Postel et al. (1996) estimate that the human appropriation of blue water is 4430 billion m^3/yr, but this does refer to total withdrawal of blue water, while WF analysis only accounts for the part of the blue water withdrawal that evaporates. The remainder will return to the surface-groundwater system. Finally, Postel et al. (1996) estimate the grey WF at 2350 billion m^3/yr, which is based on the assumption that 50% of municipal and industrial wastewater flows are untreated and a dilution factor of about 4. By accounting only for the return flows as they are, Hoekstra and Chapagain (2007a, 2008) have applied a conservative dilution factor of 1.

The global EF and WF figures show that some types of consumption (energy-intensive activities such as travelling and land-consuming products such as food) greatly contribute to the total appropriation of bioproductive space, while another core set of consumer goods (water-intensive products

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such as food and cotton clothes) contribute relatively much to the total appropriation of freshwater. A meat-based diet contributes to both higher EF and WF if compared to a vegetarian diet. Energy use of a society however strongly contributes to its EF, but not to its WF. Typical water-consuming products such as cotton or water-polluting activities such as washing in households or industries do obviously contribute to the WF, but to a less extent to the EF.

4.2. *Globally available natural capital, ecological reservation and actual appropriation*

According to the estimate by Hails et al. (2006) the global biocapacity is 11.2 billion global hectares. Monfreda et al. (2004) provided a figure of 11.4 billion global hectares. Put in this context, the current global EF of 14.1 billion global hectares already exceeds the biocapacity. When the land requirement for CO_2 absorption is not included in the EF, as some authors have argued, the utilization of the biocapacity comes to 60%.

Green water availability in the world is about 70,000 billion m^3/yr (Postel et al., 1996). The green WF of 5330 billion m^3/yr thus constitutes 8% of green water availability. This is a conservative estimate; with their wider definition of green water use, Postel et al. (1996) arrive at a figure of 26%. When estimating the remaining free green water availability one has to subtract from the green water availability a certain fraction to be reserved for maintaining natural ecosystems. An estimate of the size of such a reservation has never been made.

To establish a good measure of blue water availability is a bit difficult. According to Postel et al. (1996) about 20% of total runoff forms remote flows that cannot be appropriated and 50% forms uncaptured floodwater, so that only 30% of runoff remains for use. They argue therefore that a good measure of the available water resources in the world for abstraction and dilution—the blue water availability—could be the ‘geographically and temporally accessible runoff’, which amounts to 12,500 billion m^3/yr. The blue-grey fraction of the global WF is thus 17% of the maximally available volume. Assuming that minimally 30% of the available blue water resources have to be reserved as environmental flows, the volume of ‘free’ blue water is still more than half of the total. It is emphasised here, however, that the estimated blue-grey WF is conservative. Postel et al. (1996) estimate that human appropriation of blue water is 54% instead of 17%. Besides, research on quantifying environmental flow requirements is still in its infancy. Finally, ‘free’ blue water will be located in different places from where the demand is, and it will partly flow in the wet period while the demand is in the dry period. It may be economically or politically unfeasible to capture parts of the so-called ‘free’ flow, for instance because additional infrastructure would be required to capture and use it.

The above figures suggest that at the aggregated global level the appropriation of bioproductive space has become more critical than the appropriation of freshwater resources. However, this type of interpretation is probably a bit too early given the many issues of possible debate remaining. For instance, the total EF appears to be very vulnerable to the decision to include the area for CO_2 absorption and to the precise conversion rate assumed. The water figures are very sensitive to the assumptions about what we count as ‘available’, i.e. the way of accounting for temporal and spatial variability. Besides, the global figures tell little about what might be critical at a level below the global level. According to UNESCO (2003, 2006) for example, the current patterns of global water use already lead to unsustainable conditions in many places, as witnessed by the many reported cases of water depletion and pollution.

4.3. *National EFs and WFs*

On a per capita basis, ecological footprints widely vary among countries. While the global-average EF is 2.2 global hectares per person, there are countries with an EF of four to five times the global average (Hails et al., 2006). The United Arab Emirates have an EF of nearly 12 and the USA an EF of 9.6 global hectares per capita. At the low end we see developing countries such as Afghanistan, Somalia, Bangladesh, Malawi and Pakistan, with EFs of 30% of the global average or less. The energy-component in the EF contributes greater to the total EF for industrialized countries than in the case of developing countries. In the least developed countries the use of cropland is generally the largest component.

The world-average WF is 1240 m^3/cap/yr, but both the size and composition of national water footprints differ across countries. Eight countries—India, China, the USA, the Russian Federation, Indonesia, Nigeria, Brazil and Pakistan—together contribute 50% to the total global WF (Hoekstra and Chapagain, 2007a, 2008). On a per capita basis, it is the people of the USA that have the largest WF, with 2480 m^3/yr per capita, followed by the people in south European countries such as Greece, Italy and Spain (2300–2400 m^3/yr per capita). Large water footprints can also be found in Malaysia and Thailand. At the other side of the scale, the Chinese people have a relatively low WF with an average of 700 m^3/yr per capita. In the rich countries consumption of industrial goods has a relatively large contribution to the total WF if compared with developing countries. The consumption of industrial goods very significantly contributes to the total WF of the USA (32%), but not in India (2%).

The national EF and WF figures cannot be compared due to the fact that the EF estimates are based on global average productivities and thus reflect differences in consumption only, while the WF estimates are based on actual productivities and thus reflect differences in both consumption and productivity. As a result, a country like Nigeria can for example have a relatively large WF (due to very low yields in agriculture), while it has a relatively low EF.

5. Conclusion

The roots of EF analysis lie in the search for an indicator that can show what part of the globe's biocapacity has been used. This focus has motivated the choice to work with global average productivities and not specify the geographical spreading of a footprint. The roots of WF analysis lie in the exploration of the global dimension of water as a natural resource, by uncovering the link between water use,

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consumption and international trade. This has inspired the choice to look at the origin of products and take into account local productivities. The major methodological differences between EF and WF analysis that have grown from this different focus are:

1. EFs are most of the time calculated based on global average productivities, while WFs are calculated based on local productivities;
2. EFs are not spatially explicit, while WFs are (by distinguishing goods and services by origin)
3. the components of an EF are weighted (based on equivalence factors) before adding up to the total EF, while the components of a WF are added without weighting.

The advantage of the approach chosen in WF analysis (points 1–2) is that it includes more detail. The disadvantage is that the approach requires much more data and is thus more laborious. In the view of the author one approach is not better than the other. The meaning and therefore the use of the analytical result will simply differ depending on the method followed. The fact that the approach to calculating WFs is in some respects slightly different from what is currently mainstream in EF analysis is rather historical than fundamental. The approach followed in current mainstream EF analysis can easily adopted in WF analysis. Vice versa, as various authors have demonstrated, the approach followed in WF analysis can as easily be adopted in EF analysis (Van Vuuren and Smeets, 2000; Erb, 2004).

With respect to the outcome of the footprint estimates, one can see both similarities and striking differences. Food consumption for instance contributes significantly to both the ecological and the water footprint, but transportation and manufacturing of food (and associated energy use) is very important only for the ecological footprint. From a sustainability perspective, the water footprint of a country tells another story and thus at times will put particular development strategies in a different perspective.

6. Discussion

Although there are differences in the historical roots and adopted calculation methods and applications, the EF and the WF are similar concepts in that they aim to quantify and visualize the extent of human appropriation of the available natural capital. The EF accounts for the appropriation of natural capital in terms of the area required for human consumption and the WF accounts for this in terms of water volumes required. The one indicator can impossibly substitute the other one, simply because they provide another piece of information. They should rather be seen as two complementary indicators of natural capital use in relation to human consumption. Looking at only area requirements or only water requirements is insufficient, since land can be a critical factor in development in one case, but freshwater in another case.

Chambers et al. (2000, p.69) already observed that freshwater is an important resource that is not included in most current EF assessments. And in the few cases that it was included, one has accounted only for the forestland requirement for offsetting the emissions of CO_2 that are associated with obtaining, treating and distributing freshwater (DTI, 1997, cited in Chambers et al., 2000, p.98). Even if the land use for artificial canals and storage reservoirs would be added, the use of land associated with water use is relatively small. Measuring land use associated with freshwater use is a logic undertaking when the intention is to translate all types of natural resource use into use of bioproductive space. However, measuring land use is not an evident choice, even a very unusual and inappropriate one, when the intention is to have an indicator of freshwater appropriation in relation to freshwater availability.

The most recently developed framework of WF analysis is to be seen in the context of a much broader search for indicators and analytical approaches to assess sustainability of humanity's appropriation of natural capital. WF analysis has been compared in this paper with EF analysis, but it also relates to other analytical approaches such as carbon footprint analysis, energy analysis (Herendeen, 2004), analysis of human appropriation of net primary production (Vitousek et al., 1986; Haberl et al., 2004) and life cycle assessment (LCA) or material flow analysis (MFA)s. Frameworks like LCA and MFA take a product-or sector-perspective. An LCA or MFA is carried out for one particular product or region and looks at the use of the various types of environmental resources and impacts. In contrast, EF analysis, WF analysis, energy analysis and net-primary-production analysis take a primary-resource-perspective. These types of analyses are carried out for one particular type of resource—EF analysis looks at the bioproductive areas required, WF analysis at the water volumes required, etc.—and thereby take into account all products being consumed.

It is proposed here to see the appropriation of bioproductive space not as the only aggregate indicator of humanity's impact on the globe's natural resources. Bioproductive space is just one scarce natural resource. Freshwater and energy are others. I hope that the comparison between the two concepts in this paper enables scholars active in the area of water management to learn from the debate on ecological footprints and to enrich the ecological-footprint discussion with a water-use perspective in addition to a use-of-space perspective. A challenge for future research is to bring EF analysis, WF analysis and the other types of sustainability analysis together in one framework. One first step is to harmonise the footprint calculation methodologies and develop ways to use EF and WF estimates as complementary in assessing the sustainability of the use of natural capital by human being.

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