> The Virtual Water and the Water Footprint Concepts

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1. INTRODUCTION AND SUMMARY

Developed by T. Allen more than 15 years ago, the concept of 'virtual water' is now apparent in discussions across the mainstream media from television and radio, to newspapers and magazines. Virtual water is defined as the freshwater (from this point on simply "water") required for the production of goods or service delivery. While virtual water is actually required for production, it can be said to be non-existent in the final product (apart from a negligibly small residual amount). In this work, the author outlines the ways in which this concept has been applied and explains why its practical implementation has proved to be so difficult. Over the last ten years, an extensive amount of literature has been produced on the issue of virtual water. The data collected are usually characterised by huge fluctuation margins, even in studies of products from comparable production sites. As will be revealed, the reasons for these high fluctuation margins are, in part, contradictory. Sometimes quantities indicated are simply not exact. More often, however, highly specific numerical values are given which do not stand up to proper examination and suggest an accuracy that is actually non-existent. Accordingly, in the work presented here, quantities of virtual water have been rounded and in some cases, fluctuation margins are noted. Information about the content of virtual water in certain goods has been compiled and discussed. More comprehensive information and – unfortunately unavailable – original research would have been required to carry out a more detailed analysis of the data on the basis of distributions. As with most other publications on virtual water, this work primarily focuses upon agricultural products. This is justifiable given that 70% of global virtual water is assigned to agricultural products.

Building on the concept of virtual water, A. Hoekstra developed the notion of the 'water footprint', which indicates the entire volume of water (including the virtual water) required per time unit by one or more persons, companies, or people in particular places. The global water footprint shows the total amount of water used by all human beings in a certain time unit. Most commonly, the volume of water per year is taken as a measure. Some works leave out the time reference to relate the water footprint to the amount of a certain product. The water footprint thus defined will be identical with the content of virtual water. The meaning and application of the water footprint concept will be further exemplified here. Like the virtual water concept, the practical implementation of this concept has been problematic. It has been observed that many relevant variables have been disregarded or insufficiently taken into account. For instance, the initial concept did not consider water quality, which is at least considered in an approximate fashion in more recent works due to the introduction of the "green", "blue", and "grey" water footprint. Green, in this case, denotes reusable rainwater. "Blue" relates to ground water and surface water. The "grey" water footprint is a notional figure that characterises the degree of water pollution caused by the production of goods. Despite some difficulties, the categorisations of "green" and "blue" water footprints can be said to be useful extensions of the concept, while the introduction of "grey" water footprint notions has yet to consistently produce satisfactory results.

The virtual water and water footprint concepts are analysed and advantages and disadvantages compiled. As global trade with virtual water flows and agricultural goods has shown, over 90% of water is made up of "green" virtual water, which consists of rainfall and as such is not associated with any – or with only very small – opportunity costs. This implies that only a minute share of the virtual water traded can be critical in terms of overexploitation (in the exporting country) or conservation (in the importing country) of water resources. The concepts of virtual water and the water footprint do not make a substantial contribution to the debate on efficient water use or the challenge of sustainable water management. In particular, the concepts do not allow for an investigation of the amount of the particularly critical, i.e. unsustainably obtained, virtual water used.

Virtual water and the water footprint are stimulating concepts that allow for an analysis of global flows of virtual water. They help to illustrate that the cultivation of crop plants requires enormous amounts of water. Roughly estimated values are usually sufficient in order to give an idea of the global amount of flows. However, the work here shows that the application of these concepts to small regions requires more accurate information and further analysis. As will be shown, the usefulness of the concepts for the Berlin-Brandenburg region has thus remained limited. Without further detailed information and research, no noticeable benefit (for consumers and producers) will be gained from applying the concepts of virtual water and water footprint in the region. The existing concept is of little use in addressing questions about establishing a good water economy, sustainable land use and, more generally, a sustainable use of water as a resource.

In the work conducted here, the author proposes a broadening and modification of these concepts in the following ways. With regards to the water necessary for the manufacturing of products, this work takes into account only the share that has been withdrawn at the place of manufacture in an unsustainable way or which has been polluted beyond a certain measure. The same applies to the water required for rendering services. The advantages and disadvantages of the broadened concepts will then be discussed and a simplified method will be introduced which offers a means to at least roughly capture the water that has been unsustainably withdrawn. The modified concept identifies those sections, regions, and goods that reveal an overexploitation of water resources and quantifies this overexploitation. In this way, it yields useful information for both producers and consumers and serves as an information source for sustainable water management. The application of the modified concept to the Berlin-Brandenburg region is then discussed.

Finally, the author addresses the issue of "Global Change and Virtual Water". This results in a listing of impacts and recommendations from a global point of view. Looking forward, questions are outlined that remain open and key research needs are highlighted. The proposed concept of unsustainable virtual water requires further research and, above all, data collection.

The work is divided into eight sections. To allow readers to read sections and sub-sections individually, important definitions and major insights are repeated or pointed to explanations given in other sections.

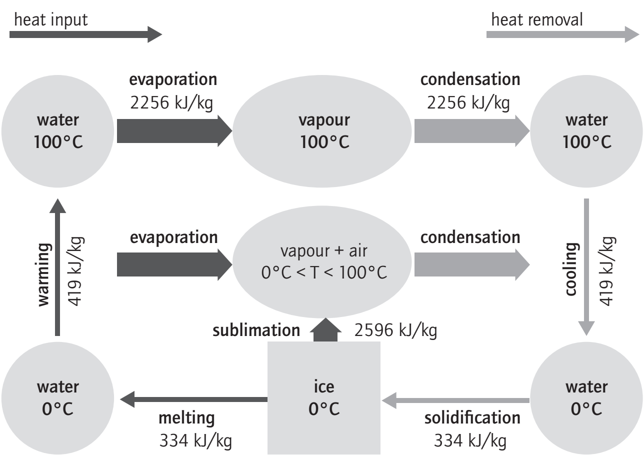
The author would like to thank Professor Dr. Hans-Georg Frede for numerous helpful suggestions and corrections.

2. GENERAL REMARKS, PRECONDITIONS, AND DEFINITIONS

2.1 WATER: IMPORTANT FEATURES

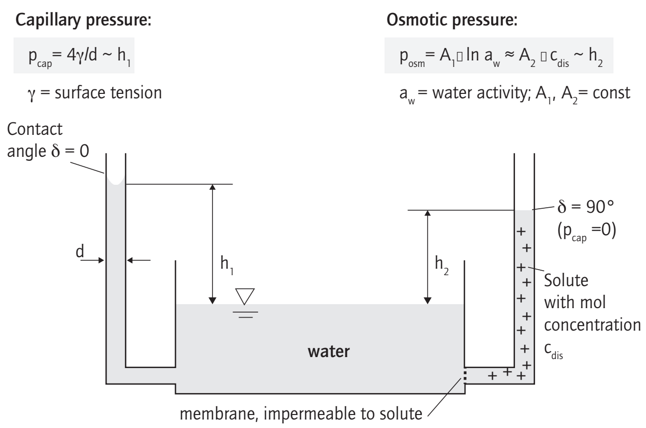
Of all the natural substances on Earth, water is the only one that exists in large amounts as a solid (ice), liquid, and gas (water vapour). It is characterised by a high heat of evaporation and a high specific heat capacity. The loss-free conversion of pure water into solid, liquid, and gaseous states at an ambient pressure of 1 bar is schematically displayed in figure 1.

Figure 1: Schematic representation of the conversion of water into solid, liquid, and gaseous states at an ambient pressure of 1 bar (without losses)



Ice can melt through exposure to heat (heat of fusion 334 kJ/kg at 0°C), water can be heated and finally evaporate (heat of evaporation 2,256 kJ/kg at 100°C). Heat removal causes steam condensation, cooling and, finally, ice formation. When heat is supplied, water vapour can be released into the atmosphere as a vapour-air-mixture. This is then referred to as evaporation or – in the case of heat removal – as condensation (e.g. in case of a formation of clouds). Water evaporation, which often provides cooling in both nature and technology, can only occur if the air is not saturated with water vapour, i.e. at relative air humidity below 100%. Conversely, water vapour may only condense in saturated air. As water vapour absorption in air increases with an increase in temperature, it is possible to influence evaporation and condensation by changing the temperature. For the sake of exact calculation, it is necessary to consider that the heat at which evaporation occurs depends to some extent on the temperature when water evaporates into a vapour-air-mixture. Finally, water vapour may also change directly from a solid to a gaseous state if the heat of sublimation is added. This process is called sublimation. The reverse process, i.e. the immediate conversion from a gaseous to a solid aggregate state, is known as resublimation. In air unsaturated by water vapour and at temperatures below freezing, water ice dries by means of sublimation. In turn, the formation of hoarfrost is an example for resublimation.

Figure 2: Capillarity and osmosis. Water activity is defined as the quotient of water vapour pressure above the solution and water vapour pressure over pure water with a plane surface (capillary pressure p_{cap} =0)



Compared to other liquids, the viscosity of water is relatively low while its surface tension is high. Its low viscosity facilitates fast in- and outflow whereas the high surface tension allows for capillary effects, the latter of which also has a major influence on water storage capacity, underground water movement (Schubert, 1982) and evaporation processes upon the soil surface. Moreover, many substances are soluble in water and, as a consequence, osmotic effects arise that may, for example, have an impact on water movement in membranes like cell walls or which can be utilised for water purification. Figure 2 elucidates capillarity and osmosis in a simplified manner. In wetted systems with a contact angle as small as possible, capillary pressure increases with a decreasing pore diameter. Osmotic pressure increases with the molar concentration of the solute or water activity (figure 2). As many substances are readily soluble in water (or by use of surfactants may be finely dispersed within it), water possesses good transportation and cleaning properties. Due to its high specific heat capacity and mobility, water has a significant influence on the global climate and numerous weather incidents. Finally, it should be mentioned that water is, in chemical terms, a highly stable substance and its indispensability to all life on earth obvious.

2.2 GLOBAL WATER CYCLE

The characteristics of water briefly outlined in the first passage of section 2.1 provide the basis for the global water cycle which obtains its energy from the sun. *(Remark: Given the fact that the accruing amounts of water are huge, specialised literature mostly refers to the annual volumes of water in km^3/yr (cf. for example Zehnder, 2002; Lehn and Parodi, 2009), but occasionally also in Gm^3/yr or Gm^3/a (Hoekstra, 2003a; Hoekstra and Chapagain, 2008). The unit km^3/yr in terms of the International System of Units (SI) defined as (km)^3/yr, may be converted as follows: 1 km^3/yr = 10^9 m^3/yr. For the SI-unit Gm^3/yr, however, the conversion 1 Gm^3/yr = 10^{27} m^3/yr is to be applied (G as an abbreviation for Giga defined as 10^9). After consulting the author Hoekstra, it has become clear that the numerical values before the measuring unit Gm^3/yr are meant to designate km^3/yr = 10^9 m^3/yr. The same applies for the unit Mm^3/yr or Mm^3/a (Chapagain and Hoekstra, 2010). Mm^3/yr is tantamount to 10^{18} m^3/yr – however, the intended meaning in the work quoted is 10^6 m^3/yr.)*

Water evaporates from the oceans (71% of the earth's surface) and land surface (29% of the earth's surface), condenses in the atmosphere through the formation of clouds and yields precipitation – which on a long-term average amounts to 110,000 km^3/yr above the land surface (i.e. 750 mm/yr in relation to the land surface). As evaporation above the oceans is 40,000 km^3/yr higher than precipitation, above land surface evaporation (70,000 km^3/yr or 480 mm/yr) is correspondingly smaller than precipitation. Given the fact that the water circuit is a closed circuit, 40,000 km^3/yr run off into the ocean on a long-term average. The numerical values mentioned are rounded data obtained through research (Endlicher, 1991; Zehnder, 2002). By means of the water circuit, water is not only permanently distributed across the earth's land surface – it is also purified as in a water distillation plant. By means of evaporation and, subsequently, condensation, the oceans' salt water is converted into fresh water.

2.3 WATER OF THE EARTH, WATER UTILISATION

While the oceans contain an almost unlimited amount of salt water, only 3% of the water on earth is available as freshwater (for the sake of simplicity, freshwater will be referred to as water from here on). Only a tiny share of about 0.1% of the earth's water (Shiklomanov, 1993; Zehnder, 2002) is stored in a way that allows for immediate access and use by nature and human beings. In order to guarantee sustainable utilisation, the amount of water stored has to remain constant over a long period. This means that precipitation is the only renewable resource available for sustainable water management.

Part of the overall amount of precipitation falls onto climatically unsuitable and thus sparsely populated areas of land and, from there, does not flow to more populated areas. Consequently, only a part of the amount of precipitation that falls onto the earth's mainland is also available to human beings. Moreover, one has to bear in mind that about 40,000 km^3/yr flow back from the mainland into the ocean (cf. section 2.2). The data available in the literature does not really provide substantiated information which would allow for an assessment of a) the share of this amount of water *actually* utilised by man as well as b) the *potentially* utilisable share in terms of technical and economic uses. We will come back to this issue later in this section. For example, one has to take into account the currently uncontrollable and thus unusable masses of water that result from extremely high amounts of precipitation and flooding as well as the possibility of multiple uses of water by means of water purification.

The type of use is of major importance. If merely the potential kinetic energy of water is used, for example in hydroelectric power stations, further utilisation will normally be possible without restrictions. The same applies more or less to the use of water for transportation purposes, for instance in shipping (however, in this case we have to consider the potential for pollution). In most other cases, though, a significant change in water quality can be expected. This applies to cases where water is used for cleaning (be it in industry, trade or private households) or irrigation purposes in horticulture or agriculture. Large amounts of water are used for cooling purposes. In this case, we have to distinguish between direct cooling using river or coastal water and evaporative cooling, for instance in cooling towers. In the case of direct cooling, the river or coastal water will be warmed and, perhaps, slightly contaminated by the addition of substances present to prevent e.g. algae infestation. If the on-site receiving water temperature is too high, evaporation cooling may be chosen instead. Typical examples are cooling towers of large thermal power plants or industrial plants where water evaporates and is thereby released into the atmosphere. In this process, the heat from evaporation (cf. figure 1) of water is used for cooling.

It is important to point out that water is usually contaminated or heated which may induce thermal pollution, but not fully consumed or used up, as is the case with fuels, electric energy, etc. Even though the purification of water can be highly complex and therefore expensive, no water will be lost from a global point of view. Nature is able to purify water by means of distillation (evaporation and condensation, cf. section 2.2), depth filtration (groundwater), crystallisation (ice formation) and other physical, chemical, and biological methods. These and other methods are also used in technology for the purpose of water purification. Membrane processes are increasingly used, for instance also for desalination of seawater by means of reversed osmosis (for this process, see fig. 2). The law of mass conservation for water

$$P + Z - R - E - \Delta S = 0, \qquad (1)$$

where P = mass of precipitation
Z = mass of inflow from upstream regions (Z = 0, if the balance scope is a river basin)
R = mass of water runoff
E = mass of evaporated water (including transpiration)
ΔS = changes in stored mass of water (positive when stored mass increases)

is valid for a certain period of time and, from a regional perspective, for a limited balance scope (control volume). However, we need to remember that the evaporated amount of water is no longer available within the control volume, whereas the water outflow may be repeatedly used and purified before finally leaving the system boundaries. As a consequence, it seems fair to refer to the amount of evaporated water as water consumption, since – at the time of evaporation – this amount is no longer available to the control volume. As the evaporated water will return to the earth's surface as rainfall at some point in time, at least a certain share (depending on the control volume's size) of this evaporated amount of water may be re-added to the respective region. This secondary effect will not be addressed in this work. (Natural) evaporation is made up of evaporation (E) and transpiration (T) and is referred to as evapotranspiration.

$$ET = E + T \qquad (2)$$

Evaporation designates the evaporation from moist solid surfaces such as soil (soil evaporation), plant surfaces moistened by precipitation (interception) or other water surfaces without biological or physiological processes. Transpiration is defined as the evaporation from plants by means of biological-physiological processes. Evaporation from sufficiently moist solid surfaces of water surfaces depends solely on the prevailing external air conditions such as temperature, humidity, air velocity as well as the radiation energy added. In soil science, this level of evaporation is referred to as potential evaporation, whereas in drying technology the same phenomenon is known as the first drying stage (cf. Mersmann et al., 2005). The surface is cooled down due to the required heat of evaporation – which is vital for plants in many dry and warm regions on earth. As soon as capillary water transport from the inside ceases to keep the solid surface (e.g. soil surface) sufficiently moist, the water level will fall from the surface down into the soil. As the process is increasingly controlled by the diffusion of water vapour to the soil surface, speed of evaporation will decrease accordingly. This level of evaporation is known as actual evaporation in soil science, or as the second drying stage in drying technology. With the solid surface's increasing dehydration, the speed of evaporation will decrease and – as regards soil – will be primarily determined by soil properties.

Evaporation occurring above the earth's land area (as mentioned in section 2.2) of about 70,000 km^3/yr is equal to evapotranspiration and may be influenced, for example, by forms of land use, the selection of certain plants or tillage. Compared to the total amount of evaporated water, man-made evaporation in cooling towers is negligibly small.

Compared to other kinds of water use, evaporation is of particular importance. This is also stressed by the following reflection: if in a certain region (control volume) water is used for manufacturing non-agriculturally produced goods or for rendering services, this water will be available for further use after sufficient purification and will finally end up in the balance scope's sewerage. For the production of agricultural goods, however, water is primarily needed for evaporation purposes – and due to its evaporation, this water will no longer be available to the region. In the case of large-scale irrigation of dry soils, the mass of evaporating water E, according to equation (1) reduces the water runoff R as long as P and Z remain constant and ΔS disappears on a long-term average (sustainability). On the whole, a large-scale cultivation of arid regions that utilises additional irrigation for agricultural purposes may eventually have an impact on the global water cycle.

Grünewald (2010) has compiled a detailed description of water balances especially for the Berlin-Brandenburg region.

In academic literature estimated values for the amount of global water that is available for human use vary. According to research conducted by Lehn and Parodi (2009), 40,000 km^3/yr is often regarded as renewable annual water resources by researchers (cf. Gleick, 2000; Lemke, 2002; Lozan et al. 2005). With regard to the current population of the earth (6.5 billion people), this equates to 6,000 m^3 of utilisable water per inhabitant per year (6,000 m^3/(cap • yr)). According to calculations by Zehnder (2002), only 9,000 to 12,000 km^3/yr of water is globally available for drinking water production, agriculture or industrial use. This is about 1,500 m^3/(cap • yr) with regard to the entire global population. According to Falkenmark (1989), this represents a value verging on water shortage. In his assessment, Zehnder (2002) decided to deduct the water that evaporates above the land area as a non-utilisable share. However, as evapotranspiration needs to be taken into account for the production of agricultural goods, Zehnder's assessments have to be revised upwards to some extent. Lehn and Parodi (2009) have already noted this problem and state that as a long-term average, an estimated 100,000 km^3 of water per annum are available as a renewable resource and thus also for human use. As a consequence, the estimated values in the academic literature as to the global amount of water annually available to human use vary between 10,000 and 100,000 km^3/yr (per capita: 1,500 to 15,000 m^3/yr ≈ 4,000 to 40,000 litres/day). Hence they fluctuate by a factor of 10. If – due to the lack of reliable data – it is assumed an average value between both extreme values, then an annual 8,000 m^3 or 20,000 litres per day of usable water per capita would be at the global population's disposal as a renewable resource. Hence, from a global perspective, water scarcity would neither be a problem today nor in the coming decades (cf. section 4.2). However, further research geared towards reducing the abovementioned fluctuation margins is needed in order to achieve more accuracy and create a more reliable database.

In order to assess the water supply to the earth's population, regional water availability is a more important indicator than global water availability. There are regions with an excess of water, regions with satisfactory or sufficient water supply, and regions that suffer from water shortage (1,700 to 1,000 m^3/(cap • yr)), water scarcity (<1,000 to 500 m^3/(cap • yr)), and extreme water scarcity (<500 m^3/(cap • yr)) (Falkenmark and Widstrand, 1992). Finally, we have to consider the temporal dimension of water availability. Dry periods during the growing season have an impact on the yield by hectare in agriculture and may be compensated by additional irrigation. Given the current state of technology, we are unable to transport the huge amounts of water across large distances in an efficient way. Thus efforts to balance these disparities by means of direct water transport are hardly an option – at least as long as there is no natural slope available. States' using rivers for water supply (the main source of which may also be located outside their sphere of sovereignty) is an example of direct water transportation. Due to economic reasons, the transport of water (e.g. by ship) from regions with water excess to remote regions suffering from water scarcity (e.g. to irrigate agricultural areas) is not a feasible solution at this stage. Regions unable to carry out sufficient farming on their own (e.g. due to water shortages) therefore depend on importing raw materials for food and fodder from abroad. The lion's share of water utilised by humans is needed for food production, as plants require huge amounts of water from seed to harvest. As will be shown, about 1,000 to 10,000 kg of water is needed in order to produce 1 kg of foodstuff. In other words, it is either possible to transport 1 kg of food or to transport the thousandfold to ten-thousandfold mass of water to an arid region which will then be able to produce the raw food materials on its own. These thoughts lay the foundation for the concept of virtual water.

3. THE VIRTUAL WATER CONCEPT

3.1 DEFINITIONS

Virtual water can be defined as the water that is required for manufacturing a product or for rendering a service. Virtual water also contains the actual amount of water that exists in a certain product, particularly since this water was also necessary for the production of this good. For our purposes, electrical energy is also to be regarded as a product. *(Note: Although this declaration is not correct in a legal sense, it is nonetheless appropriate in this context. To the author's knowledge, the academic literature does not give a satisfactory answer as to how electric energy should be considered in defining virtual water. The production of electric energy can require considerable amounts of water. As regards the data mentioned in sections 3.2 and 3.4 and the literature from which it emerges, it remains largely unclear whether the import and export of electricity has been properly considered.)*

In 1994, Allen was the first to introduce the concept of virtual water in London (Allen, 1994; World Water Council, 2004). It was based upon analyses by Israeli water experts who found that it seemed to make more sense for their arid country to import water-intensive goods than to cultivate (or even export) them themselves (World Water Council, 2004). Import mainly refers to commodities such as cereals. High-quality and thus costly agricultural raw materials may be produced at home as long as proportionate water costs remain sufficiently low.

Allen, a hydrologist, had initially developed the concept of virtual water as a metaphor – but then attempted to apply it in order to illustrate the actual amount of water utilised by humans. Moreover, the concept allows us to track the flows of virtual water, since trade with goods whose production requires large amounts of water can be understood as a virtual transfer of water. This kind of transfer is referred to as virtual water trade (Hoekstra, 2003a, World Water Council, 2004). As soon as a water-intensive agricultural product is exported, the exporting region will lack the amount of water required for evapotranspiration, whereas the importing region will save this amount of water. Section 5.1 will elaborate on these issues in more detail.

In everyday language, 'virtual' is often misinterpreted as 'fictitious' or as the opposite to 'real'. As used here, however, 'virtual' is a notional quality that exists in its effects rather than in a physical sense. The concept of 'embedded water' (which was coined before 1994) has not managed to gain acceptance. Today, 'virtual water' (sometimes also denoted as 'hidden water') has become a popular concept in scientific research and beyond. Mass media such as print and electronic media have reported on virtual water and information guides have been distributed for educational purposes (Bayerisches Staatsministerium für Umwelt und Gesundheit, 2009).

3.2 APPLICATION OF THE CONCEPT

Although at first glance the concept of virtual water appears to be simple, it has proved difficult to practically apply it. Firstly, it is necessary to make a distinction between services and products. In terms of service, it remains an open question as to what extent water demand should also consider the virtual water needs of the person who renders this service. The same applies to products that are utilised by service providers. In the case of products, we have to consider the type of water use. When the form of utilisation of water is the sole source of its contamination, reutilisation will be possible as soon as the water has been purified. Water demand at a certain production location (and thus also water demand per product) can be reduced substantially by means of appropriate recirculation with integrated waste-water treatment. Water that evaporates into the atmosphere will however be lost for the respective system and can thus be regarded as consumed in a regional sense (cf. section 2.3). Hence, the majority of water demand that is required for household purposes, for manufacturing industrial products, or the treatment and processing of raw materials into food products needs to be assessed in a different way to the amount of water which is needed for evapotranspiration to generate agricultural raw materials. Ordinarily, the majority of the water utilised by industry, trade or households will be contaminated, while only a small share will be released into the atmosphere due to evaporation or sublimation. This feature has hitherto been insufficiently discussed within the context of discussions on the concept of virtual water.

Another difficulty comes about from the question of how to consider the type and quality of water. While this issue had been initially disregarded when the concept of virtual water arose, experts have come to classify water into "green", "blue", and "grey" water (as explained in section 4.3) and thus – at least to some degree – have started to take into account the origin, type, and quality of water (Mekonnen and Hoekstra, 2010a, 2010b and 2010c). "Blue" water, for instance, consists of both groundwater and surface water. Due to its different possible conditions, it can be utilised for the production of raw food products to varying degrees at different locations. Therefore, water conditions ought to be incorporated into the concept of virtual water. Until now, however, the potentially necessary purifications of water and the related costs have not been considered. What is still missing is a suitable approach to assessing virtual water that manages to take into account water quality in a satisfactory way.

Two different definitions have been suggested in the attempt to provide a more detailed description of virtual water (Hoekstra, 2003b). According to the first definition, virtual water denotes the water that is actually required for manufacturing a certain amount of a product at the respective site of production (production-site definition (Hoekstra and Chapagain, 2008)). According to the second definition, it is defined as the water that would be necessary for manufacturing the same amount of the same product at the place where the product is eventually needed (consumption-site definition (Hoekstra and Chapagain, 2008)). The first definition refers to the producer's perspective, while the second refers to the perspective of consumers. The work presented here departs from the first perspective, as long as there is no explicit reference to the second definition.

The amount of water needed for the production of agricultural goods (Hoekstra, 2008) as well as industrial goods (Dehler, 2010) may considerably depend on the production site. For example, let us assume that the amount of water required for manufacturing the same amount of the same product is three times higher in country A than in country B. In this case, the export of the same amount of this product from A to B would involve a threefold transfer of virtual water compared to an export from B to A. Consequently, product transfer from A to B implies that A loses three times the amount of virtual water that B would save if it produced the same amount of the same product in its own country. In a standard work, Hoekstra and Chapagain (2008) displayed the connections between water use and international trade upon the basis of extensive data.

Goods cannot be produced at every location in a sensible way. In Germany, for example, rice and coffee plants do not thrive in the open land. In order to be able to compare the virtual water of agricultural products from various sites, Renault (2003) suggested referring to similar products of equal nutritional value. Such an approach even allows for estimating the virtual water content of seafood that live in salt water and thus do not require (fresh) water. According to this approach, a far from insubstantial 8% of global virtual water is to be assigned to sea products (Renault, 2003). Generally, it can be said that the extraction of biomass from seawater might be an option to address the potential problem of water scarcity. It is possible to use algae for animal feed, as sources of energy or even for human nutrition; in fact, these options are already being researched (Posten and Schaub, 2009).

In the attempt to allow for a systematic comparison of the water required for the production of goods, it is customary to refer to the volume of the required water in relation to the product's mass. If 1,000 litres of water are required for 1 kg of a certain product, the following equation applies to the obtained volume v of virtual water:

$$v = 1{,}000 \text{ litres of water}/(\text{kg of a product}) = 1{,}000 \text{ litres/kg} = 1 \text{ m}^3/\text{kg} = 1{,}000 \text{ m}^3/\text{t}$$

The product may either be a primary (e.g. a freshly harvested coffee bean), intermediate (roasted coffee bean), or final product (coffee ready to drink). As research data for the abovementioned example (Hoekstra, 2008) reveals that the volume v obtained may fluctuate by a factor of 10, a precise designation of the product is necessary. As a matter of fact, inaccurate product descriptions are the cause for much of the incomprehensible data related to virtual water. The virtual water volume v refers to the product mass and as such is often labelled as a product's virtual water content. If the entire plant's mass portion is large in relation to the harvested valuable part of the plant (as is the case with cocoa, coffee, and cotton plants), this will result in high values of virtual water per mass of the harvested good (i.e. high virtual water contents).

As a means to illustrate the high water demand, virtual water is sometimes also related to other product volumes such as a cup of coffee or a cotton T-shirt. For the purpose of general assessments, virtual water may also be related to a product's price. As for foodstuff, referring to nutritional values or energy content are other possible options (Renault 2003). In the case of electrical energy, it is appropriate to relate virtual water to a unit of energy (like kJ or kWh) even though a mass-based reference (e.g. to crude oil or coal equivalents) would be possible, too.

The concept of virtual water is, in part, similar to the life cycle assessment (LCA) that is applied to analyse a product's impact on the environment. The methods for generating LCA's have meanwhile been refined (ISO-Norm 14040) and can be said to be much more comprehensive than the concept of virtual water, for example, with regard to sustainability assessments (Finke, 2008). To the best of this author's knowledge, thus far the concept of virtual water has not been developed along the lines of LCA (cf. Hoekstra, 2003b).

The water required by plants during the growing season is also well researched in soil science (cf. Blume et al., 2010). The nexus of water consumption by evapotranspiration ET and plant yields is expressed by the evapotranspiration coefficient ETC, which describes water consumption caused by evaporation (ET) in relation to the plant dry mass produced throughout the entire growth period.

ETC = ET/dry mass = kg water/kg dry mass

In the case of sufficient water availability, the rounded mean values of ETC for some native plants amount to 200 for potatoes, 350 for winter wheat, and 450 for French beans. These figures come from field experiments that were conducted in the Thuringian basin (Roth et al., 2005). ETC is strongly dependent on the length of the total growth period of the cultivated plant. Although referring to the dry mass of the product appears as useful as choosing a dimensionless factor, both have remained rare in the academic literature on virtual water.

In what follows, we will primarily deal with the virtual water of agricultural raw materials. This seems justifiable given that 70% (Hoekstra and Chapagain, 2008; Wefer, 2010; UBA, 2011), the great majority of water utilised by humans, is used for the agricultural production of raw products that are required mainly for food production.

For crop plants, virtual water is mainly determined by evaporation occurring during the timespan between sowing and harvest. For plants such as rice, the period of field preparation immediately prior to sowing or planting will be added (Chapagain, Hoekstra, 2010). Above all, evapotranspiration is responsible for determining the amount of virtual water contained in the final product. Compared to the product-related amount of water needed for evapotranspiration, the water required for treatment and processing amounts to only a few percentage in the case of modern enterprises in food industry (Brabeck-Letmathe, 2008). Evapotranspiration primarily depends on factors such as the type of plant and its water demand, water availability, meteorological data at the respective location, and the form of land management. In the case of artificial irrigation, water management, the type and efficiency of irrigation will have an essential impact on defining the amount of virtual water per harvested product. The amount of evaporated water above vegetated land surfaces can be determined with the aid of empirical equations (cf. Dietrich and Schöninger, 2008). In general, this will, however, usually yield highly unreliable estimated values. The virtual water content of a product can be generated by comparing the area-related water content of crops (m^3 water/ha) to the harvest of the respective agricultural area. It becomes obvious that as the harvest increases, the content of virtual water will decrease. For instance, due to an annual rise in output of 3%, global cereal production has tripled between 1960 and 2005, while the area of cultivation has remained more or less constant throughout this period (cf. Fuchs, 2009). While the total amount of evapotranspiration has not changed significantly, this implies that the virtual water content has decreased by a factor of three throughout the abovementioned time period.

It is important to precisely define the product to which virtual water is to be assigned in each particular case. If the harvested material is to be used for different purposes, the virtual water should be assigned proportionally to the respective sub-quantities. For cereals we would have to differentiate between the grains (or the flour produced thereof) on the one hand and straw as well as husks (that may be used for the production of energy) on the other. The single sub-quantities may be assigned in terms of either weight or value. Research has not always taken into account the set of problems connected to these issues. We should, however, consider them, as the content of virtual water will vary by a factor of 2 or more according to the assignments mentioned above.

In most cases, the virtual water content of animal products is significantly higher than the virtual water content of crop products. Animals need to be fed and watered throughout their lives. In terms of animal housing, additional water will be required for cleaning purposes. For agricultural production, the predominantly vegetarian feed requires large amounts of water that will be allocated to the animal products as virtual water. The total amount of real and virtual water required by the animal and the water required for processing are proportionately allocated to the diverse animal products (meat and sausage products, eggs, milk, cheese). This proportional allocation may also occur in terms of weight or, more frequently, by using the market value. For ready-to-eat animal products, research data (Mekonnen and Hoekstra, 2010b) suggest an estimated 3,000 to 15,000 litres/(kg product) of virtual water content, as against about 1,000 to 3,000 litres/(kg product) for ready-to-use crop products. As the virtual water content is significantly higher for cotton, coffee beans and cocoa beans, these plants clearly constitute an exception. Values for some other selected products are displayed in table 1 and table 2 below.

The following reference values are applicable to ready-to-eat food (Brabeck-Letmathe, 2008):

Ca. 10 litres of water for 1 kcal (4.2 kJ) of meat,
ca. 1 litre of water for 1 kcal of vegetable food.

Accordingly, a global average of about 3,000 litres of water per adult person per day are thus required for foodstuff. (The energy supply recommended per day and adult person is about 2,500 kcal ≈ 10,000 kJ).

Numerous parameters, simplifications and various understandings can have a considerable influence on the estimated amount of virtual water content. In general, there is a lack of information on the reliability of the estimated values published. The value for the ascertained virtual water is composed of several appraisal values and this leads to the question of whether a modified 'Fermi-solution' (cf. Peleg et al., 2007) might possibly help to improve the validity of data. The Fermi-solution is a quantitative assessment of a value that is made up of several sub-evaluations and is computed by calculation methods as simple as possible. The accuracy of the Fermi-solution is based upon the experience that some of the assumed sub-evaluations will be too high while others will be too low. As a consequence, the error margin for the desired value will be kept low. These calculations often involve distributions and thus usually require experience in dealing with distributed variables.

The sometimes inexplicably wide variations when assessing virtual water contents have recently been discussed in the academic literature (Lischeid, 2010).

Table 1: Water demand (virtual water) for selected products

PRODUCT	VIRTUAL WATER IN litres	CONTENT OF VIRTUAL WATER IN litres/kg product
1 cup of tea (250 ml)	35	140
1 glass of beer (250 ml)	75	300
1 glass of wine (250 ml)	240	1,000
1 cup of coffee (125 ml)	140	1,100
1 slice of bread (30 g)	40	1,300
1 slice of bread with 10 g of cheese	90	2,300
1 egg (40 g)	135	3,400
1 "hamburger" (150 g)	2,400	16,000
1 cotton T-shirt (200 g)	2,000	8,000
1 microchip (2g)	32	16,000

Resource: Hoekstra and Chapagain, 2007.

Table 2: Content of virtual water for selected products

PRODUCT	VIRTUAL WATER CONTENT IN litres/kg product	
	FOR DIFFERENT COUNTRIES	GLOBAL AVERAGE
Sugar cane	100 – 200	170
Maize	400 – 1,900	900
Milk (cow)	650 – 2,400	1,000
Wheat	620 – 2,400	1,300
Soybeans	1,100 – 4,100	1,800
Rice	1,000 – 4,600	2,900
Chicken meat	2,200 – 7,700	3,900
Pork	2,200 – 7,000	4,900
Beef	11,000 – 21,200	15,500
Coffee (roasted)	5,800 – 33,500	20,700

Resource: Hoekstra and Chapagain, 2007.

Note: Processing is seen to cause the high content of virtual water v for roasted coffee beans. For the coffee fruit (coffee cherry) after harvesting, v ≈ 2,800 litres/kg (global average, Hoekstra and Chapagain, 2008). As only the seeds (beans) of the coffee cherry can be used while the pulp will be discarded, the ground potential will be reduced. In turn, the virtual water content will increase accordingly. Drying during the roasting process will further increase the content of virtual water. In contrast, the contribution of the water required during processing to the virtual water content of roasted coffee beans remains negligibly small – even in the case of wet processing (ca. 10 litres/kg coffee cherry). Thus, it is not true that processing coffee requires large amounts of water, as is sometimes claimed.

4. THE WATER FOOTPRINT CONCEPT

4.1 DEFINITIONS

Water footprint is defined by the total volume of water that is required per time unit for a person or a particular group of people. It comprises both the directly required volume of water and the specific indirect (i.e. virtual) amount of water for manufacturing goods or providing services that are required by that particular person or group. The water footprint is typically expressed in annualised terms. It is also customary to refer to cities, regions, states, or companies where goods are manufactured or services provided.

There are different options for determining the water footprint. On the one hand, it may be estimated upon the basis of the total volume of virtual water of all goods and services claimed by a certain region. On the other hand, it may be calculated by using the amount of all water resources claimed by a certain region, plus the virtual water imported and minus the virtual water exported by this region. The latter method is most commonly used. An ever more comprehensive collection of data has been worked out by the "UNESCO-IHE Institute for Water Education" in Delft and the Dutch universities in Delft and Twente in Enschede (cf. Hoekstra and Chapagain, 2008). In 2008 the "Water Footprint Network" (WFN, 2008) was established which provides extensive research on the issues of virtual water and the water footprint.

As for global trade, the water footprint of nations provides another useful variable. For example, Germany's water footprint has been measured at 125 km^3 water/yr ≈ 4,000 litres of water/(cap • day) (Hoekstra, 2008). Other assessments (Sonnenberg et al. 2009) provide estimated values of 160 km^3 water/yr ≈ 5,000 litres of water/(cap • day). Further, it should be remembered that depending on the applied definition of the water footprint, different dimensions will arise, such as

m^3 water/(person • yr),
m^3 water/(enterprise • yr),
m^3 water/(region • yr), or
m^3 water/(nation • yr).

In recent research, the author of the water footprint concept has suggested applying it to products and services as well (Hoekstra, 2008). A product's water footprint is to be defined by the volume of water required for manufacturing a certain mass of this product at the actual place of manufacture. Usually, the water footprint thus defined will be indicated in m^3 water/kg product. As Hoekstra notes, this definition is in line with the definition of the virtual water content. However, it always refers to the place of manufacture so as to allow for a regional reference point. The same applies to services offered.

4.2 APPLICATION OF THE CONCEPT

The water footprint concept was coined by Hoekstra (Hoekstra and Hung, 2002). It is an extension of the virtual water concept and was developed with reference to the ecological footprint (cf. Wackernagel and Rees, 1996) and the ecological backpack (Schmidt-Bleek, 1993). It is meant to serve as an indicator for the direct and indirect use of water by both consumers and producers. Water footprint does not, however, merely indicate the amounts of water utilised by humans. Instead, it is also meant to illustrate the location or region where water needs to be available for products and services and where consumers demand it (Hoekstra, 2008). The following example helps to explain the concept of the water footprint. An average inhabitant of country A may require an annual 100 kg of foodstuff from country B, where 200,000 litres of water are needed in order to produce this food. As this particular share of its overall consumption of foodstuff had to be imported first, the consumer can be said to leave an annual water footprint of 200,000 litres of water in country B.

The global water footprint for agricultural products amounts to 7,500 km^3/yr, which equals 1,200 m^3 of water/yr (≈ 3,300 litres/day) per capita of the global population. The yearly water footprint per capita varies between 700 m^3 (China) and 2,500 m^3 (USA). These data refer to the time period of 1997 to 2001 (Hoekstra and Chapagain, 2007) and approximately correspond to more recent data (7,400 km^3/yr) collected for the inquiry period 1996 to 2005 (Mekonnen and Hoekstra, 2010a). For the earlier period of inquiry 1971 to 2000, the global water footprint for agricultural products (also see section 5.1) was estimated to come to 8,500 km^3/yr based upon a model calculation (Rose et al., 2008). In view of the wide variations, the abovementioned global mean value (3,300 litres/day and capita) corresponds quite well with the estimated value mentioned in section 3.2 (3,000 litres/day and capita). If the global water footprint of 7,500 km^3/yr is related to the earth's total mainland surface (ca. 1.5 • 10^8 km^2), the value 50 mm water/yr is obtained, which is small in comparison to the global amount of precipitation (750 mm/yr) falling on the earth's mainland (see section 2.2).

If it is assumed that agricultural products are responsible for 70% of the global water footprint (cf. section 3.2), the total global water footprint will amount to 10,500 km^3/yr (4,600 litres of water per capita and day). Related to the earth's total mainland surface, this is equivalent to 70 mm water/yr, i.e. less than 10% of the global amount of precipitation falling on the earth's mainland.

In order to develop a better idea of the origins of the water utilised in a certain country or region, it has proven useful to differentiate between an internal and external water footprint. The internal water footprint is defined as the time-referenced volume of water that is required for producing goods and providing services as well as for domestic use within the same time period in the respective country. The external water footprint refers to virtual water that finds its way into this country by means of an import of goods or services throughout the same period of time. Table 3 clearly illustrates the internal, external and total water footprint for the Federal Republic of Germany. Unfortunately, there is a lack of reliable information concerning the accuracy of the data. Research on virtual water flows for industrial products (Dehler, 2010) show variations of more than 30% compared to the data for the industrial products sector cited here. This may serve as a reference value for the fluctuation margins of the estimated values.

Table 3: Internal, external, and total annual water footprint for Germany, calculated for the years 1997-2001. The values are rounded values and relate to estimated values by Hoekstra and Chapagain (2008). *The values in brackets displayed in italics show the originally published data that suggest a degree of precision that is unrealistic.*

INTERNAL WATER FOOTPRINT 10^9 m^3/yr	EXTERNAL WATER FOOTPRINT 10^9 m^3/yr	TOTAL WATER FOOTPRINT 10^9 m^3/yr
60 *(59.86)*	70 *(67.09)*	130 *(126.95)*

The data in table 3 demonstrate that Germany – as a leading exporting country – imports goods and services whose production requires more water than is actually utilised for the domestic production of all goods and for the provision of all services. This may be due to several factors, e.g. high efficiency in domestic production and management compared to the countries from where the virtual water is imported. We will return back to this set of problems in section 5.1.

4.3 "BLUE", "GREEN", AND "GREY" WATER FOOTPRINTS

"Blue" water refers to groundwater and surface water. "Blue" water is readily available to humans. It may be collected and transported and is, for example, used in agriculture for artificial irrigation. In contrast, "green" water is capillary water in the soil or stored in plants. It results from precipitation and is utilised for local farming and forestry. As a long-term global average, 65% is available as "green" water, while 35% is available as "blue" water (Zehnder, 2002). However, huge regional and (due to drought periods and floods) also temporal variations occur.

As already mentioned earlier, water is usually not consumed. Instead, the use of water usually results in contamination or – in the case of cooling water (direct cooling) – warming. Only the water that evaporates into the atmosphere can be said to be consumed as it is usually no longer available to the respective region. In contrast, contaminated "blue" water may be purified in sewage treatment plants and therefore re-used once or several times.

"Green" and "blue" water are used in agriculture. According to Falkenmark (2003), used "green" water is defined as water that results immediately from precipitation and is consumed through evaporation (mainly through evapotranspiration). The utilised share of "blue" water originates from groundwater and/or surface water and is also consumed through evaporation (mainly through evapotranspiration and evaporation in the supply system). The water that has percolated into the soil is not classified as utilised or consumed water, because it will be re-added to the system as groundwater (cf. section 4.4).

In general, the utilisation of "green" water does not apply to industrially or commercially manufactured products and services. According to Hoekstra and Chapagain (2008), the share of "blue" water contained in these products is defined as the share of the utilised water that is released into the atmosphere as a consequence of evaporation or sublimation, and since it cannot be expected to return to the region considered (control volume), it may be regarded as consumed. (Note: although evaporation and sublimation are not explicitly mentioned in research, they are certainly considered implicitly). The same applies to service provisions and the water used for domestic purposes.

Contaminated water is frequently referred to as “grey” water. In many countries, it is utilised in agriculture after (or without) purification. In Germany, this form of water utilisation is rejected for hygienic reasons (Lischeid, 2010). Academic literature does not make a distinction as to whether the contaminated water is bound in the soil or whether it is easy to manage and therefore can be purified in sewage treatment plants (as is the case with “blue” water).

The share of “grey” water is defined differently in the water footprint and virtual water concepts (Hoekstra and Chapagain, 2008). In general, the production of goods involves a contamination of water. As a measure for contamination, Hoekstra choose the volume of water that would be needed to dilute the contaminated water to an extent just about sufficient to reach a tolerable standard concentration c_{max} of undesired substances (Hoekstra and Chapagain, 2008). The dilution water related to the product mass is defined as the share of “grey” water.

$$v_{grey} = m_s / (m_p \cdot c_{max}) \qquad (3)$$

In this equation, m_s indicates the mass of undesired substances contained in the water per year (kg/yr), while m_p refers to the mass of the product manufactured per year. Together with the share of the utilised, product-related “green” (v_g) and “blue” (v_b) water, the total content of virtual water can be summarised with the following equation:

$$v = v_g + v_b + v_{grey} \qquad (4)$$

Correspondingly, the following equation illustrates the total water footprint

$$WF = WF_g + WF_b + WF_{grey} \qquad (5)$$

In general, the “grey” water footprint and the “grey” virtual water content are to be regarded as notional variables that serve as a guide for water quality and as such do not always need to be provided as real amounts of water. In contrast, “green” (in the case of agriculture) and “blue” virtual water do have to exist as real amounts, since they are used for production purposes. For these reasons, it is problematic to add the share of “grey” water in the equations (4) and (5) in order to determine the total share of virtual water or the virtual water footprint – even if this has come to be accepted in the academic literature. This issue will be returned to in section 6.

The “grey” share is questionable if the manufactured good is not an agricultural product, since contaminated water is usually treated in sewage plants and not “purified” by means of dilution. Dilution should not be considered a measure to sufficiently characterise the effort required for the purification of water. For a certain share of “grey” water, purification in sewage plants is usually not an option and an acceptable water quality can be achieved through dilution instead. This share of water may be of significance for harvested agricultural products. However, for soil water, the content of contaminates (e.g. caused by ineffective fertilisation or plant protection products) will also be reduced through other mechanisms and largely depends on the type of contamination as well as the respective farmland. The determination of a tolerable standard concentration c_{max} of contamination should similarly be regarded as problematic. Therefore the dilution approach is problematic in terms of agricultural products. Nonetheless, it may be acknowledged that this approach provided a preliminary means of assessing water quality in terms of virtual water content and the water footprint.

The share of utilised “green” water (v_g or WF_g) is unproblematic for both the environment and the farmer. Green water is supplied immediately through precipitation and in general does not result in any (or very little) opportunity costs, meaning that hardly any potential revenues may be lost due to an alternative utilisation of this water. Depending on the comparison with alternative forms of utilisation of rainwater, even negative opportunity costs might be achievable (Lischeid, 2010).

The share of utilised “blue” water may, however, be problematic. Sustainable water management becomes possible in a region for which the water-influx is sufficiently high (due to direct precipitation or due to an inflow from upstream regions) on a long-term average when compared with the total amount of evaporation. However, as soon as the amount of “blue” water that is withdrawn or released into the atmosphere (by means of evaporation) exceeds the amount of water that can be re-added on a long-term average, a deficit emerges. As a consequence, water management will cease to be sustainable. Many regions around the world often resort to artificial irrigation, thereby utilising water in an unsustainable manner (Hahn, 2009). In some cases, this has engendered a dramatic lowering of the ground water level or shrinkages of inland waters, such as the Aral Sea (Giese et al., 1998). This is why we must pay special attention to the virtual “blue” water content and the “blue” water footprint. What is the maximum share of “blue” water we may utilise in a certain region without endangering sustainable management? Unfortunately, research data fail to answer this crucial question so far.

As already mentioned, according to Hoekstra (Hoekstra and Chapagain, 2008) "grey" water generally indicates a notional value that helps to describe water conditions in a very simplified manner. In the production of agricultural products, the share of "grey" water can be kept low by means of optimising the use of suitable fertilisers and plant protection products. With the aid of novel engineering methods, mineral fertilisers are nowadays formulated in ways that allow for a plant-specific, delayed release of substances exactly when they are required. The same applies for the technical formulation of plant protection products that need to be broken down quickly. Although product design by using the latest technical formulations is still far from being applied everywhere or in an optimum manner, this trend will continue as it helps to save costs compared to the substances previously used. Organic fertilisation – which is likely to contribute the highest share to the "grey" water footprint in the future – is exempt from this development. Rice growing poses challenges, too (Chapagain and Hoekstra, 2010) and therefore can also be expected to create a "grey" water footprint in the future. Finally, leaching salt out of the soil may require a substantial amount of water (Frede, 2010).

As already indicated earlier, the share of "grey" water (defined, following Hoekstra and Chapagain (2008) as clean water used for the dilution of dirty water) is not to be regarded as a helpful variable in the case of industrially or commercially manufactured products. To the knowledge of the author, reliable information on the "grey" water footprint of industrially or commercially manufactured goods is not yet available.

4.4 PERCOLATION AND THE WATER FOOTPRINT

A recently published work (Chapagain and Hoekstra, 2010) mentions percolation alongside "blue", "green", and "grey" virtual water in the context of rice growing. At times, it also specifies the share of percolating water that results from precipitation and the "blue" water used for irrigation. As percolating water is immediately re-added to a water catchment area and thus will be available for re-utilisation, it cannot be assigned to virtual water or the water footprint. However, it does provide information regarding the amount of water that is required in agriculture in relation to soil structure and other parameters. Table 4 clearly illustrates the average agricultural production of rice for 33 countries (covering 98 % of the worldwide production of rice) throughout the years 2000 to 2004.

Unfortunately, we lack data on the respective levels of precipitation. Assuming an annual precipitation level of 750 mm of water and a total area of arable land of $1{,}500 \cdot 10^9 m^2$ (Chapagain and Hoekstra, 2010), 1,900 litres of water/kg rice would be available per product volume. In contrast, only $v_g + v_b \approx 1{,}200$ litres of water/kg rice are consumed through evapotranspiration. Taken as a global average, sustainable water management for rice cultivation is thus in principal possible. As is stated by the abovementioned authors, in a global perspective the share of "blue" water required for irrigation is relatively high in countries such as the USA and Pakistan. Drawing conclusions at a global level are therefore inappropriate and misleading. Instead, regional conditions need to be considered.

The numerical values mentioned here concerning the average annual precipitation levels can only serve as a preliminary, rough guide. It should be noted that many rice-cultivating regions of the world have adapted rice growing to rainy seasons that yield high amounts of precipitation (Frede, 2011).

Table 4: Content of "green" (v_g), "blue" (v_b), "grey" (v_{grey}) and total amount of virtual water ($v_{tot}=v_g+v_b+v_{grey}$) and the share of percolating water (v_{per}) required for the agricultural production of rice. The values are displayed in litres of water per kg rice for an average annual production of $590 \cdot 10^6$ t rice within the reference period 2000 – 2004. The rounded numerical values were determined by the original data from Chapagain and Hoekstra (2010).

PRODUCTION 10^6t/yr	v_g litres/kg	v_b litres/kg	v_{grey} litres/kg	v_{tot} litres/kg	v_{per} litres/kg
590	630	580	110	1,320	1,030

5. ASSESSING THE VIRTUAL WATER AND THE WATER FOOTPRINT CONCEPTS

5.1 TRADE IN GOODS AS AN INDICATOR OF VIRTUAL WATER TRANSPORTATION

Trade in goods necessitates the transport of these products. However, this obviously does not involve the transportation of the sometimes tremendous amount of virtual water required for manufacturing these commodities. The transportation of virtual water between regions and nations is defined as virtual water flow. As already mentioned in section 3.1, virtual water flow is a notional value, whereas virtual water really has to exist and needs to be utilised at the time when a good is being produced. The amount of virtual water exported by a country is referred to as virtual water export. This value denotes the water that was required at the place of production for the production of exported goods or the provision of exported services. The virtual water import refers to the virtual water imported by a country due to an import of products or services from abroad. For a specified period, it is possible to devise a balance for virtual water flow. The virtual water balance of a certain country is defined as positive (net-import) if more water has been imported as exported. In the reverse case (net-export), one speaks of a country's negative virtual water balance for a specified period. These concepts – which can only be briefly sketched here – have been described at length in the academic literature and have been quantified through a great deal of research on international trade flows (Hoekstra and Chapagain, 2008). Table 5 provides an example. America is the region with the biggest net-export of virtual water worldwide, with the shares being near equally apportioned between North and South America. By contrast, Europe (especially Western Europe (with 150 $\cdot 10^9$ m^3 water per year) as well as Central Asia and South Asia are the regions with the highest net-import of virtual water. As the specifications on the amounts of virtual water only represent roughly estimated values, the data provided can, however, only provide a general picture of virtual water flows.

As data delivered by other authors (Zimmer and Renault, 2003) indicate, the values tend to fluctuate enormously depending on various estimates. Accordingly, caution is required. Table 6 presents an example. Even in cases where data are not immediately comparable, the order of magnitude at least ought to correspond to some extent (cf. tables 5 and 6).

Table 5: Net-flows of virtual water per year for selected regions of the globe (reference period: 1997-2001). The rounded data (Hoekstra and Chapagain, 2008) relate to the trade with agricultural products.

DONATING REGIONS (REGIONS WITH NET-EXPORT)	10^9 m^3/yr	BENEFICIARY REGIONS (REGIONS WITH NET-IMPORT)	10^9 m^3/yr
America	-215	Europe	170
Australia and Oceania	-70	Middle and South Asia	150
Africa	-65	Middle East	50
Southeast Asia	-30	Former USSR	10

Table 6: Net-flows of virtual water per year for selected regions of the globe (reference year: 1999). The rounded data (Zimmer, Renault, 2003) relate to the trade with agricultural products.

DONATING REGIONS (REGIONS WITH NET-EXPORT)	10^9 m^3/yr	BENEFICIARY REGIONS (REGIONS WITH NET-IMPORT)	10^9 m^3/yr
North and Central America	-150	European Union	7
South America	-120	Asia	244
Australia and Oceania	-110	Africa	50

While the figures mentioned correspond to a satisfactory extent in the case of donating regions, deviations are much too high for the beneficiary regions of Europe and Africa. While Hoekstra and Chapagain (2008) see Africa as a donating region, Zimmer and Renault (2003) consider it a beneficiary region. This strongly varying and in part contradictory information on amounts of virtual water or water footprints is typical of the academic literature (cf. also Lischeid, 2010). In this author's opinion, the more recent research illustrated in the abovementioned example can be expected to contain more reliable data, particularly as it builds on the older data mentioned (and larger amounts of data in general) for analysis.

Apart from trade with virtual water, one may also look at the storage of agricultural raw products or foodstuffs in terms of virtual water storage. According to research conducted by Renault (2003), the global sum of stored crops amounts to a virtual water volume of 500 km^3 or 830 km^3 if the storage of sugar, meat and oil is added. The latter value is equivalent to 14% of the quantity of water contained by water reservoirs or 11% of the annual global water footprint. Once all cattle and sheep living on earth are also included, this corresponds to a virtual water volume of 4,600 km^3 (77% of the water reservoirs available or 61% of the global annual water footprint) (Renault, 2003).

According to the published estimated values, Germany is one of the net-importers of virtual water. The spread for the published net-flows of virtual water reaches from $1 \cdot 10^9$ m^3/yr (harvested products 1999, Zimmer and Renault, 2003) up to $32.1 \cdot 10^9$ m^3/yr (harvested products 1997-2001, Hoekstra and Chapagain, 2008) or $30.73 \cdot 10^9$ m^3/yr (all agricultural products 1997-2001, Hoekstra and Chapagain, 2008). Apart from the high fluctuation margins, it is also typical of most all the research published on virtual water and the water footprint to specify numeric values to several places after the decimal point, thereby providing an accuracy that simply does not exist. For instance, statistics indicating a total annual water footprint of 159.5 cubic kilometres for Germany or a daily consumption of 5,288 litres of water per German citizen (Sonnenberg et al., 2009) are not reliable and should at least be rounded off (cf. section 4.2).

A nation can preserve its own water resources by importing water-intensive goods or services. On the whole, water will be saved if the virtual water content of an imported product is smaller than the virtual water content of the same product if it had been produced at home. In the opposite case there will be an overall loss of water. Initially, one of major objectives of virtual water transportation was the movement of agricultural raw products from water-rich regions to arid regions. This was intended to protect water resources in arid and semi-arid regions and to save water overall. On a global scale, about 5% of the water required for production is saved through the international trade of agricultural products today (Hoekstra and Chapagain, 2008). Given that virtual water is determined in reference to the product mass (i.e. the virtual water content), we need to consider that these savings do not have to be the result of reduced consumption due to evapotranspiration. Instead, savings may also be achieved by a higher yield per area. The production of agricultural goods in countries with unfavourable conditions for irrigation, poor water management and inefficient farming entails high virtual water contents and will result in high water consumption per product unit. Conditions of this kind are often found in poor countries that lack the necessary means for sustainable water management and efficient farming. Notwithstanding that the transport of harvested commodities from regions with efficient water management and farming to these countries helps to save on water from a global point of view, the results are not satisfactory. It would certainly be more beneficial to increase efficiency of water management and agriculture in regions with a potential to do so. As is shown in the example, global savings on water according to the concepts of virtual water flows or water footprints are not always desirable – especially if water is saved in regions where water is not a scarce resource.

5.2 THE WATER FOOTPRINT

As outlined in section 4.1, 'water footprint' is a concept that is immediately understandable - the amount of water used per time measure by a certain entity. "Entity" may refer to a person or a group of persons as well as to companies, regions or nations. However, water footprint may also be defined as the utilised amount of water per amount of a certain product. In this case, the concept is identical to the virtual water content (section 4.1). Water footprint manages to avoid the term 'virtual', though, which is often misinterpreted by the public. The particular meaning is specified by respective dimensions, like m^3 water/(person • yr), m^3 water/(region • yr), or m^3 water/(kg product). If, for instance, a consumer buys an imported product, he will leave a 'footprint' in the exporting country according to the amount of water that was required for this good's production in the exporting country.

The following correlation has already been noted: the poorer the water management and the less effective the production in the exporting country is, the higher the water footprint per product mass will be. The water footprint concept is also founded on the idea that it elucidates the responsibility of both producers and consumers for water demand (Hoekstra and Chapagain, 2008) with the aim of reducing it. The water footprint concept allows producers to compare their own water demand with the water demand of their competitors in a way which encourages greater efficiency. However, as long as blue water remains highly subsidised (as is the case in many countries of the world) and as long as it is customary to utilise blue water almost for free (as in farming), the concept of the water footprint will be of little use in reducing water wastage and water consumption. Although consumers are not able to exert a direct influence here, the virtual water and the water footprint concepts may, however, help to raise awareness of the high water consumption of each and every one of us, especially in highly developed countries.

Our eating habits – and especially the amount of meat consumed – have an impact on our personal water footprint. Under favourable conditions and in case of a daily food energy input of 10,000 kJ and vegetarian diet, a minimum of 230 m^3 of water per year (630 litres per day) are required for a person of normal weight. If the share of meat is 20%, though, the required amount will increase to 640 m^3 of water per person and year (about 1,700 litres of water per day) (Zehnder, 2002). As a rough estimate, an additional 50% of virtual water will be required as a result of a) the usual crop losses and post-harvest losses, b) the water demanded for the production of foodstuff and c) food waste. As a consequence, the annual water demand per capita required for nutritional purposes will be 350 m^3 (about 1,000 litres of water per day) for vegetarians. For a mixed diet with a 20% share of meat and meat products, it will amount to 1,000 m^3 of water (2,700 litres of water per day) (Schubert, 2007). As the indicated values are minimum estimated values, we can expect the average water consumption per capita to be slightly higher (Brabeck-Letmathe, 2008). As the example illustrates, the personal water footprint resulting from a mixed diet is 2-3 times higher than for a vegetarian diet. As such, consumers' eating habits have a substantial influence on water consumption.

With some exceptions, experience shows that providing information like this does not lead to significant change in people's eating habits. This even applies to the expensive informational campaigns on how the high consumption of meat in Germany and other affluent countries of the world may result in health disadvantages for the consumers. It is, therefore, doubtful whether the water footprint concept can help to influence consumers' decisions. Nevertheless, brochures on virtual water or the water footprint keep on appealing to 'new insights' ("*Through our buying behaviour, we can actively contribute to ... fighting water shortages ... in other countries*") (Bayerisches Staatsministerium für Umwelt und Gesundheit, 2009) or the conscience of consumers (*'Virtual water' is proof that we are having a good time at the expense of the water balance in other regions".*) (BBU, regioWASSER, 2006). It should be noted that Germany is one of the net-importers of virtual water (section 5.1). It is not enough, however, to pose the general question about where our water really comes from (as is done by the BBU brochure). It is crucial to ask what kind of water we are talking about. This will be addressed in the following.

When looking at the trade of goods, research usually considers virtual water flows without making a distinction between "green", "blue", and "grey" water. Instead, studies usually depart from the total volume of virtual water that is being virtually shifted between regions and nations. Only recently have authors begun to differentiate between "green", "blue", and sometimes also "grey" virtual water flows. By modelling, Rost et al. (2008) have provided global values for the total (WF), "green" (WF_g), and "blue" (WF_b) water footprint for agricultural products in the period 1971 to 2000 as follows (rounded data):

WF_g = 7,200 km^3/yr (85 %)
WF_b = 1,300 km^3/yr (15 %)
WF = 8,500 km^3/yr (100 %)

In comparison to these figures, the "green" water footprint for grasslands was said to be 8,000 km^3/yr, while the water footprint for the remaining vegetation amounts to approximately 45,000 km^3/yr. The "grey" water footprint (WF_{grey}) according to Hoekstra's definition (section 4.3) was not considered. The total water footprint WF is slightly higher than the value mentioned in section 4.2 (7,500 km^3/yr), but remains within the necessary margin of accuracy. Approximately half (700 km^3/yr) of the "blue" water footprint required for field irrigation comes from non-renewable resources (e.g. fossil groundwater) or from upstream regions that do not belong to regions of the respectively considered nations. This means that less than 10% of water resources are to be regarded as particularly critical for the production of agricultural raw materials.

In a definitive work on the global water footprint (Hoekstra and Chapagain, 2008), the following data are provided for all goods (rounded value figures):

WF_g = 5,300 km³/yr (72 %)
WF_b = 2,100 km³/yr (28 %)
WF = 7,400 km³/yr (100 %)

As for the production of harvested products, the authors provide the following data:

WF_g = 5,300 km³/yr (83 %)
WF_b = 1,100 km³/yr (17 %)
WF = 6,400 km³/yr (100 %)

In a recently published work (Mekonnen and Hoekstra, 2010a), the following data were calculated for the global water footprint of harvested products (reference period 1996 to 2005, rounded data):

WF_g = 5,800 km³/yr (78 %)
WF_b = 900 km³/yr (12 %)
WF_{grey} = 700 km³/yr (10 %)
WF = 7,400 km³/yr (100 %)

Adding the (notional) "grey" water footprint in order to determine the total water footprint appears questionable for the reasons mentioned in section 4.3 (cf. also section 6). When compared to the data calculated by Rost et al. (2008) or Hoekstra and Chapagain (2008), deviations remain within the usual scope of fluctuation margins for such estimated values. The two most recently compiled water footprints refer to the total amount of harvested products and do not differentiate as to what share is utilised in the producing country and what share is available for international trade.

In an interesting work, the share of "green" virtual water compared to the total amount of virtual water utilised by international trade with harvested products throughout the time period 1998 – 2002 was found to be approximately 94% (Liu et al., 2009). "Green" virtual water originates from renewable precipitation and does thus not entail any – or only little – opportunity costs (cf. section 4.3). As a consequence, this suggests that merely 6% of virtual water flows (or global water footprints) caused by international trade could be critical in terms of an overexploitation of water resources in the exporting country. Notwithstanding that further research is needed to substantiate the calculated value of 94% share of "green" water, it is clear that it is necessary to limit the significance of the total amount of virtual water flows for the overexploitation (exporting country) or the protection of own resources (importing country). Still, there are countries and regions whose water management is neither sustainable in terms of their own needs nor with regard to their export of agricultural and other products. The current conceptualisations of virtual water and water footprint do not provide information on the share of non-sustainable water in virtual water flows nor in a product's level of virtual water; and neither does it help to determine those regions with an overexploitation of the resource water. Given the fact that it is not necessary to purchase water at cost-covering market prices in many regions of the earth due to subsidies, this information would be useful not only for producers but also consumers. Producers could improve water management. Consumers could acquire information about the goods and the source countries that are associated with an overexploitation of local water resources. The present conceptualisations of virtual water and water footprint are unable to do this. As will be explained in section 6, it is thus more useful to employ modified versions of these concepts.

5.3 THE WATER FOOTPRINT CONCEPT FOR REGIONS

5.3.1 THE CONCEPT FOR SMALL REGIONS

There is an extensive literature on the water footprint of nations and large regions, which has been partially compiled in the "Water Footprint Network" (WFN, 2008). As already mentioned, the data are rough estimates values that provide an assessment of the virtual water flows among nations and large regions. Moreover, the data collected on the virtual water content of different goods give an impression of how much water is needed to produce a certain amount of a particular good at a particular place. As several other parameters have to be considered beyond the required amount of water (cf. section 5.2), it has been difficult to interpret the collected data. Here again, the specified data are estimated values that are subject to substantial regional and temporal fluctuations. Furthermore, it would be necessary to indicate the decisive parameters, such as the respective type of land use (in case of agricultural products) and the efficiency of production or water management. From a global point of view, this knowledge might suffice for a preliminary overview. However, if a small region is studied with the aim of suggesting possible courses of action, much more detail is required. To the author's knowledge, such detailed studies still do not exist. Similarly, the calculation of characteristic values of quantified or methodically collected distributions are not apparent in the literature on virtual water and water footprints. Generally, it is impossible for the farmers of a small region to draw adequate information from the – however calculated – mean values for the water footprint. For questions concerning the globalisation of water (Hoekstra and Chapagain, 2008), the concept of virtual water may, nonetheless, be useful. This is especially true if the objective is to avoid producing water-intensive goods in countries where water is particularly scarce. These issues will be addressed later.

5.3.2 UTILITY OF THE CONCEPT FOR THE BERLIN-BRANDENBURG REGION

Berlin-Brandenburg has the lowest volume of precipitation of all German regions. Two detailed discussion papers introduced the landscape water balance (Lischeid, 2010) and the water balances (Grünewald, 2010) of this region. On a long-term average (1961 - 1990), precipitation in this region amounts to 550 – 650 mm/yr, which is about one-third less than the average precipitation in Germany (860 mm/yr) (Grünewald, 2010). The region's long-term average total water balance results from the data compiled in table 7. (Note: the calculations depart from the assumption that the amount of water stored in the region has remained constant throughout the considered time period).

Evaporation consists of evapotranspiration (493 mm/yr) and the evaporation (11 mm/yr) of water utilised by industry, trade and private households (84 mm/yr), 73 mm/yr of which ultimately ends up in drains after purification. The data are always displayed in mm^3 water per year and mm^2 surface of the region (30,368 $km^2 \approx 30.37 \cdot 10^{15}$ mm^2). For comparison, table 8 contains the data for Germany with its surface of 357,112 km^2 (SÄBL, 2010).

In particular, the comparatively low volume of precipitation is unfavourable for agriculture. Nonetheless, artificial irrigation of fields has ceased to be relevant for the Berlin-Brandenburg region. After German reunification, subsidies for irrigation were abolished (Kahlenborn and Kraemer, 1999). Since then the price of water has been determined in a cost-covering way according to the EU Water Framework Directive. For these reasons, watering is no longer economically profitable and is an option only for particular crops (Lischeid, 2010). With the exception of these special cases, it becomes clear that hardly any "blue" water and almost only "green" water is used for crop production in the Berlin-Brandenburg region these days. This is true of Germany as a whole (data from 2007), since less than 0.1% of renewable "blue" water is agriculturally utilised – compared to 2.7% for public water supply, 3.8% for mining and the manufacturing sector (including industry), and 10.4% for thermal power stations (only 3% of this water will evaporate, though); 83.1% remain unused (UBA, 2010).

This water balance is undoubtedly favourable compared to the water balance of many arid countries in the world. However, the values indicated are average values. Especially during the main growing period, temporal and regional water shortages can occur. This may engender a competition for groundwater between public water suppliers on the one hand and either industrial or agricultural stakeholders on the other (Steiner et al., 1996). Besides, it should be noted that water run-off can be utilised only in part, since it is important to allow for run-off as quickly as possible (e.g. in case of floods) when no sufficient storage capability is available. This is why it is important to keep up efforts to improve water management through achieving sufficient water storage.

From a global perspective, the Berlin-Brandenburg region is very small. As shown in section 5.3.2, many detailed studies would be required to apply the current conceptualisations of virtual water and water footprint in a targeted manner. To the author's knowledge, findings which go beyond simple estimates are still not available. Moreover, crop production is almost exclusively based upon the utilisation of "green" water, which is hardly connected to any opportunity costs. In summary, Lischeid (2010) has already concluded that the concept of virtual water is of little use for managing land use in the Berlin-Brandenburg region. With reference to the current versions of virtual water and water footprint, the author agrees with this assessment.

Table 7: Water balance for the Berlin-Brandenburg region according to data provided by the Landesumweltamt Brandenburg in 2000 (long-term average 1961-1990, quoted after Grünewald, 2010)

INFLOW TO THE REGION (mm/yr)		PRECIPITATION (mm/yr)		EVAPORATION (mm/yr)		OUTFLOW FROM THE REGION (mm/yr)
344	+	617	=	508	+	453

Table 8: Annual water balance for Germany on a long-term average, 1961 to 1990 (cf. Grünewald, 2010)

INFLOW TO GERMANY (mm/yr)		PRECIPITATION (mm/yr)		EVAPORATION (mm/yr)		OUTFLOW FROM GERMANY (mm/yr)
199	+	859	=	532	+	526

6. PROPOSAL FOR A MODIFIED CONCEPT OF VIRTUAL WATER

6.1 LIMITATIONS OF THE CURRENT CONCEPT

The initial concept of virtual water did not distinguish between "green", "blue", and "grey" virtual water. Even in the most recent literature, descriptions of water footprints of nations and virtual water flows have referred to the total amount of virtual water. This appears justified with regard to the global virtual water trade or with regard to the question of what total volume of water an arid nation saves (or gives away) when agricultural goods are imported (or exported). The concept was then extended by the introduction of "green" and "blue" water. As is evident from the data compiled in section 5.2, more than 80% of the water utilised for the production of harvested crops is renewable "green" water that comes from precipitation. If we only consider the internationally traded harvested crops, the share of the green water footprint is even higher (94%) according to research data (section 5.2). As already mentioned, the concept of virtual water has frequently been used in an attempt to influence consumers and reduce their consumption of imported products which require large volumes of water to be produced. If solely "green" water was needed for the agricultural production of such goods, these efforts would not be justifiable, as rainwater entails no or only minimal opportunity costs. On the contrary, however, the utilisation of rainwater for agricultural products creates a benefit for the exporting country that would usually not exist without this agriculture. Coffee plants cultivated in climatically favourable regions with sufficient precipitation are a good example of a sensible use of "green" water for comparatively expensive export goods. Even if artificial irrigation is necessary, it does not have to be detrimental as long as sustainable water management can be warranted in this region (e.g. sustainable coffee production in the context of the Sustainable Agriculture Network (SAN)). The current concepts of virtual water and the water footprint provide no answers to these related questions. They may even lead to misguided attempts to influence consumers and might impair the export potential of economically poor developing countries. Furthermore, the water footprint concept does not allow for an adequate assessment of production conditions – and for these reasons, the Federal Environmental Agency has avoided taking a clear stance on the water footprint thus far (Markard, 2009).

Similarly, the current virtual water and the water footprint concepts have been shown to be of little use concerning questions about appropriate and sustainable forms of land use, effective water management, avoidance of water wastage and more general questions concerning the sustainable use of water. However, differentiating between "green" and "blue" water footprints is not sufficient, as "blue" water may also have a renewable share that is available for sustainable utilisation.

6.2 A MODIFIED CONCEPT TO COMPLEMENT AND EXTEND THE CURRENT CONCEPT

With reference to what has been said before, the author suggests complementing and modifying the concept of virtual water as follows: only the share of water required for the production of goods or the provision of services that has been unsustainably taken from (or contaminated to a certain extent at) the site of production or the place where the service is provided is to be defined as virtual water. The share of water utilised on-site in a sustainable fashion to produce the respective good or to provide the particular service shall not be taken into account. The modified concept thus refers to the unsustainably utilised share of water, which therefore will also be referred to as 'unsustainable virtual water' or 'unsustainable water footprint' hereafter. The main difficulty with the concepts lies in the quantification of sustainable water use, which cannot be determined by a single indicator (Hoekstra and Chapagain, 2008). Detailed descriptions of sustainable water management have shown that it is necessary to consider a number of aspects and that a plethora of open research questions still exists (Kahlenborn and Kraemer, 1999). Nevertheless, we attempt to take small steps in order to move closer to our objective. For the time being, water pollution will be excluded.

"Green" water used by agriculture that is consumed by means of evapotranspiration is to be regarded as sustainably utilised and thus remains unconsidered. "Blue" water in a producing control system (e.g. an agricultural holding, a company, a free trade, a region or a nation) may be used in a sustainable way as well. In this case, the unsustainable water footprint will disappear. As no unsustainable water flow exists in this case, the virtual water flow is not taken into account when considering the trade of such goods. For example, although drinking a cup of coffee implies utilising 140 litres of water in the producing country (cf. table 1), this water would, if there were no coffee plants, flow out of the region or would be consumed by vegetation not used by humans. In this approach, virtual water flows are not considered due to sustainable cultivation and a presumption of sustainable processing. In this context, it is important to mention that in this case the producing country does not suffer any disadvantage from the internal or external utilisation of its water resources. On the contrary, profits are gained from the production of coffee and its potential export.

To achieve sustainable water management as described here, it is a basic prerequisite that – as a long-term average – the amount of water withdrawn from a certain system (control volume) due to evaporation and water run-off must not exceed the amount of water added by inflow and precipitation. In other words, the amount of water stored in a certain system has to remain constant as a long-term average – and, for instance, the groundwater level must not decline over time. An adequate amount of water run-off is required in order to avoid a concentration of undesired substances in water beyond certain limit values. If the basic requirements mentioned are not met, the water resource is not seen to be managed in a sustainable manner. In this case, the evaporated "blue" water has to be considered as virtual water (just as in the previous concept) or unsustainable virtual water.

Taking water pollution into account is, however more difficult. For the purposes considered here, pollution is defined as all the inputs of substances that are undesired for the subsequent utilisation of water. For the agricultural sector, Hoekstra (cf. Hoekstra and Chapagain, 2008) has suggested applying the "grey" water footprint or the amount of "grey" virtual water (see section 4.3) as a measure for the degree of pollution. In general, the share of "grey" water is a notional value, which indicates the imagined volume of water required for diluting the contamination to a previously agreed level. Despite the problems discussed in section 4.3, this definition shall be adopted for the modified conceptualisation as long as only the agricultural sector is under consideration. Section 4.3 revealed that different categories are required for the water that is contaminated through use in industrial or commercial production. The same applies to the service sector. In the end, it is necessary to quantify the effort required to purify contaminated water. This issue requires much more examination, but will not be discussed in more detail here as this work mainly focuses on agricultural products, which, as stated, account for the majority of the demand for virtual water.

As the interpretation of available data on virtual water and the water footprint of harvested products demonstrates, there is a plethora of data on "green", "blue", and (in more recent publications) also "grey" virtual water. However, no data are available as to the volume of unsustainable "blue" virtual water. The author therefore argues for gathering together (or building upon) the existing data. As a first step, the water balance of a respective region may be used to observe whether the amount of water stored in this region remains constant (if so, sustainability is possible) on a long-term average or whether it decreases instead (leading to water stress and unsustainable water management). Some regions are already known to suffer from water stress (cf. Boßler and Stobel, 2009). Once a region has been identified where the water withdrawn due to evaporation and water run-off exceeds the amount of water added by inflow and precipitation, the evaporated share of "blue" water in the total amount of "blue" water utilised for irrigation purposes is referred to as unsustainable virtual water. Additional information on "grey" water according to the definition by Hoekstra (section 4.3) can be useful to characterise the degree of water contamination in agriculture caused by fertilisers and plant protection products. A summation of both types of water is problematic (cf. section 4.3) and cannot be recommended. While the evaporated "blue" water has to actually be utilised, "grey" water (according to Hoekstra) remains a notional value that is not really added to a certain system – and for these reasons cannot be part of the water balance.

As there are no reliable data about the share of sustainably withdrawn "blue" water, the following simple assessment is made in order to exemplify the modified concept. According to the numeric values mentioned in section 5.2 for the global water footprint of harvested products and in line with the most recent literature (Mekonnen and Hoekstra, 2010a), the "green" water footprint WF_g amounts to 5,800 km^3/yr, while the blue water footprint WF_b amounts to 900 km^3/yr. If we assume that slightly more than 50% of "blue" water (about 500 km^3/yr) has been withdrawn in an unsustainable way, this quantity would constitute an unsustainable global virtual water footprint. Related to the total water footprint (6,700 km^3/yr; the "grey" share should not be included due to the abovementioned reasons), this corresponds to 7%, i.e. less than 10% of the total water footprint.

Recently, the following rounded data on the global agricultural animal production (disregarding the share of "grey" water) were published (Mekonnen and Hoekstra, 2010b): WF_g = 2,100 km^3/yr, WF_b = 150 km^3/yr. According to the abovementioned assumption, 80 km^3/yr of the "blue" water footprint would result from unsustainable water withdrawal, i.e. 4% of the entire water footprint for the global agricultural animal production.

If, in addition, one bears in mind that the "blue" water footprint (6%, Liu et al., 2009) of globally traded agricultural raw products amounts to only half of the size of the "blue" water footprint (13%) of the globally produced agricultural raw products, the relatively small share of "blue" water in the production of exported agricultural products becomes evident. Each of the percentage values in brackets refers to the share of the "blue" water footprint in the total water footprint. Together with the mentioned 'guesstimate' for the share of the unsustainable water footprint, a value is obtained of about 200 km^3/yr (ca. 3% of the total water footprint) as the unsustainable water footprint for internationally traded agricultural raw products.

With the aid of research on the unsustainable share of "blue" water that results from the production of goods or the provision of services, these very rough estimates could be replaced by more reliable data. Moreover, these data should be complemented by appropriate specific values characterising water contamination as a result of the respective forms of utilisation. Nonetheless, the estimated values at hand already help to qualify published data on the apparently very high anthropogenic "water consumption" (an individual water footprint of several thousands of litres of water per day). "Green" and, in part, also "blue" water are also required by the animal and plant worlds also without interventions by humans and are part of the earth's global water cycle. Previous uses of the virtual water concept have frequently advised that we are able to counteract water shortages in other countries, or contained reproaches as to the exploitation of their water resources (section 5.2). However, these arguments tend to oversimplify matters. The modified concept suggested here only takes into account the volumes of water that have been contaminated or unsustainably withdrawn from the respective balance scope. In this way, the "consumption" of virtual water will be reduced by a factor of 10 and confines itself to the amount of water that has to be diminished in order to avoid increasing water shortages in the time to come.

Although the generally estimated unsustainable global water footprint of 500 km^3/yr (or 200 km^3/yr for agricultural raw products) is small compared to the total water footprint, huge volumes of water are still be discussed that amount to ten (or four) times the volume of water contained in Lake Constance, Germany. The reduction of the water required by agriculture to the critical share of water suggested here is designed to allow us to highlight water problems in a more targeted way than is presently possible. Water is a scarce resource in both temporal and regional terms. It is already apparent that many areas suffer from serious water shortage or are threatened by water crisis (Hahn, 2009). If no action is taken, the availability of water will deteriorate and may have disastrous impacts on both landscapes and human beings (Giese et al, 1998). The proposed concept provides a first step for counteracting this development by documenting the cases and regions where water resources are utilised in an unsustainable fashion. It helps identify, for example, the goods produced in regions that require more water than is actually available in the long-term.

The modified concept complements and extends the previous concept and has two main advantages:

1. Producers and producing regions can see if they withdraw water in an unsustainable manner through the production of goods (and when so, how much). They are thus also given an indication of the water pollution they cause.
2. Consumers and the importing regions receive information on the production processes which are based on an unsustainable use of water resources and learn about the extent of this water demand.

For both consumers and producers, the modified concept identifies the sectors, regions and goods that are responsible for an overexploitation of water resources and helps to quantify this overexploitation.

6.3 THE MODIFIED CONCEPT AS A SOURCE OF INFORMATION FOR SUSTAINABLE WATER MANAGEMENT

If it is assumed that all data are reliable and have been collected with care, the modified concept still only provides information rather than instructions for action. It thus remains an open question as to whether these pieces of information may finally also promote a more careful management of water resources. However, a broad-based diffusion of information that also reaches consumers might help support courses of action towards more sustainable water management and may help to exert at least gentle pressure on all market participants. Still, it should be stated that cost-covering market prices for all customers (including rural economies in all countries) would certainly be a more effective measure to bring about a more efficient use of water. Although this problem has been discussed for decades (cf. Hoekstra and Chapagain, 2008), an internationally accepted solution is not yet in sight.

Another way to meet this challenge is the concept of "Integrated Water Resources Management (IWRM)", which was introduced by the "Technical Committee of the Global Water Partnership (GWP)" (cf. Rahaman and Varis, 2005). IWRM is an interdisciplinary management approach tackling challenges related to water. It aims to promote measures for sustainable water management with the involvement of all affected groups and relevant stakeholders. In doing so, water resources are considered within the context of the entire ecological system. The United Nation's organisations dealing with water issues along with other organisations are conducting research in the field of IWRM. The German Society for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit, GIZ) offers national and international consulting in this area. Integrated Water Resources Management (IWRM) is a general principle which may in particular help countries affected by water shortage to reduce excessive water consumption and water pollution. The concept of virtual water does not make a substantial contribution to these aims. In some cases, one can even expect adverse developments, as is shown by the conclusions of an extensive study providing evidence that virtual water trade is neither feasible nor desirable for poor, arid, agricultural countries belonging to the group of traditional developing countries (Horlemann and Neubert, 2006).

The concept of unsustainable virtual water proposed here can help identify regions whose water withdrawal is currently too high. Moreover, it allows for a quantification of water consumption as well as pollution. The author agrees with an assessment made by the Federal Environmental Agency (Markard, 2009): *"Instead of demanding a mere reduction of virtual water consumption as such, we believe it is more important to ensure that savings are achieved where a high consumption of water has the most serious negative consequences for human beings and nature"*. Further, the potential for water-saving measures is especially high for poor arid countries, as these countries generally lack efficient water management altogether. It is poverty and insufficiently effective controls that do most harm to the environment. Support from rich countries and interested enterprises is therefore essential.

Sustainable water management is largely based upon sustainable agriculture. Firms in the food industry depend on high-quality agricultural raw products that cannot be produced permanently without high-quality water or the principle of sustainability (cf. Schubert, 2007). For these reasons, the platform "Sustainable Agriculture Initiative, SAI" has been established (Jöhr, 2003). Founded by the biggest European companies in the food industry, 18 more companies have decided to join the platform as members (SAI platform, 2007). The globally operating companies within the food industry have recognised the important role sustainable water supply of agriculture plays for guaranteeing high-quality agricultural raw products. For this reason, effective water management and a sustainable use of water are apparently the top priorities of the biggest company in the food industry (Nestlé, 2007). The provision of water of adequate quality is thus the key to feeding people and will increasingly become a limitation on the provision of agricultural products (Schubert, 2007). Depending on time and place, water is frequently a scarce resource. Today, more than one billion people are lacking access to water that does not contain health risks, and more than one third of mankind does not even have access to basic sanitary services (UNDP, 2005). Such data indicate that apart from energy provision, the provision of water of adequate quality is one of the biggest global challenges.

6.4 APPLICATION OF THE MODIFIED CONCEPT TO THE BERLIN-BRANDENBURG REGION

The following remarks apply exclusively to the agricultural sector, which – as already mentioned – represents 70% of virtual water worldwide. As outlined in section 5.3.2, irrigation of agricultural areas is currently not relevant to the Berlin-Brandenburg region (Lischeid, 2010). Accordingly, evapotranspiration of "blue" water utilised for irrigation is negligibly small compared to the total amount of evapotranspiration. Even if this tiny share is recognised, it can still assume that the "blue" water currently used for an agricultural irrigation of fields is taken from sustainable utilisation – especially as cost-covering water prices are to be charged. As renewable "green" water results from precipitation and is thus assigned to sustainable utilisation (cf. section 6.2) and considering that the tiny amount of irrigation water does not have an influence on the sustainable water management, it follows that no unsustainable virtual water exists in the agricultural sector of the Berlin-Brandenburg region. Accordingly, the unsustainable water footprint is equal to zero. The following comparison further illustrates this. Even if no agriculture at all existed in the region, there would still be vegetation, which would presumably entail no less, possible even more evapotranspiration than today.

Thus far agriculture-induced water contamination caused by ineffective fertilisation or plant protection products has not been considered. Water contamination can have a substantial impact on sustainable water use. To the author's knowledge, no data on "grey" water (according to the definition by Hoekstra (cf. section 4.3)) are available for the agricultural sector in the Berlin-Brandenburg region. Therefore, it is not possible to provide a more detailed assessment of this issue.

Although no water footprint for agricultural raw products is available for the region, it is nonetheless desirable to point to some challenges. As already mentioned, the Berlin-Brandenburg region has the lowest precipitation of all German federal states. This creates problems especially in dry years, when a lack of "green" water is accompanied by crop shortfalls. Climate change may further exacerbate these problems, as will be shown in the following section. As a consequence, existing efforts have to be continued or even increased if sustainability in general is to be guaranteed and the future supply of sufficient amounts of high-quality water in particular.

7. GLOBAL CHANGE AND VIRTUAL WATER

7.1 CONSEQUENCES AND RECOMMENDATIONS FROM A GLOBAL PERSPECTIVE

Virtual water is mostly required for agricultural products, industrially or commercially manufactured products as well as for the provision of electricity. While research frequently mentions virtual water used for the purpose of service provision, research on this issue is incomplete (cf. section 3.2) and as such it also remains unexamined in this work. Owing to modern production methods – that combine effective water management with water circuit recirculation and water treatment – the content of virtual water in industrially or commercially manufactured goods can be kept to a minimum. While we need to consider water contamination (section 3.2), only the evaporated and sublimated amounts of water qualify as water consumption. The biggest volume of virtual water is required for the production of agricultural goods that will be subsequently used for the production of foodstuff. The subject addressed here is therefore illustrated using the example of virtual water that is required for producing raw food materials of vegetable or animal origin.

In many regions of the world, food is scarce - more than 800 million people are suffering from hunger and each year, 35 million people also die from hunger (Leitzmann, 2001). Even so, from a global viewpoint, there is no shortage of raw materials for food today. Instead, we face distribution problems and poverty in many developing countries (cf. Schubert, 2007). Frequently high and avoidable post-harvest losses in many developing countries as well as the needless spoilage and the high share of food that is thrown away still offer a potential that could be – at least in part – exploited. However, many indicators suggest that we cannot assume a surplus of agricultural raw materials to exist in the future. The following facts and arguments serve to underline these doubts:

The world’s population will continue to grow from 6.5 billion today to about 8 billion in the year 2025 (UN, 2007), while the agriculturally utilisable area (i.e. the area supplied with water) will decrease. According to Hopp (2002), 0.51 ha of land were available per capita in the year 1950. In 1975, this value had dropped to 0.37 ha/cap – and in 2025, an estimated 0.15 ha of utilisable farmland is expected to remain per capita. Despite an ever-increasing efficiency of agricultural production, it is questionable whether the shrinking exploitable land area will suffice to provide enough amounts of food for the entire population in the future. The sustainably available amount of water is the limiting factor for the land area’s usability.

Western eating habits – which are characterised by high meat consumption – are increasingly adopted by emerging and highly populous countries such as China and India. Compared to a vegetarian diet, mixed diets with a 20% share of meat require twice to three times the amount of virtual water (section 5.2) or utilisable land – mainly for the cultivation of fodder cereals.

To an increasing extent, raw materials for food have come to compete with renewable raw materials, especially in the form of energy crops as a substitute for fossil fuels. Brazil has already replaced a quarter of the fuel required for vehicles by bioethanol made from sugarcane (FNT, 2006a). 13% of Germany’s farmland is being used for renewable raw materials (FNR, 2006b) – and according to projections, this share is likely to double by 2030 (FNR, 2007). The threat of insufficient supply of foodstuffs has already been recognised (Schaub and Vetter, 2007).

On the basis of data available, it is not possible to make reliable predictions about how we can expect climate change to affect the worldwide production of raw food materials. For the region of Berlin-Brandenburg, we can assume that climate change is likely to have a negative rather than a positive effect on the agricultural sector – at least if we agree to the common prediction according to which extreme events like floods and longer drought periods are likely to become more frequent, while the amount of precipitation during the growing period is expected to decline (Hüttl et al., 2011).

On the whole, the facts compiled and scenarios predicted indicate that the age of agricultural surpluses is about to come to an end. If no effective countermeasures are taken, we can expect foodstuffs to become scarcer and therefore more expensive in the future. In this context, the water required for the agricultural production of raw materials for food serves as the limiting factor. In the future, agriculture needs to be sustainable if it is to be successful in the long term. This principle particularly applies to the required water. The concept of unsustainable virtual water introduced here will help to identify and quantify the unsustainably withdrawn water utilised for the provision of goods. The author therefore recommends gathering data according to the modified concept of virtual water, i.e. collecting data on unsustainably withdrawn amounts of water that have been utilised for production purposes in important regions and nations.

Also in the future, it is probable that economic constraints in poor countries, absent or insufficient controls and other factors will lead to an overexploitation of water resources for producing goods. If additionally accompanied by emergencies such as food shortages, the principle of sustainability will be all the more violated in the attempt to produce agricultural raw products (by means of irrigation) – regardless of whether the amount of water consumption exceeds the amount that is supplied through precipitation and water inflow. As is illustrated by the examples highlighted in section 4.3, such developments may be tolerable in the short-term, but not at all in the long term.

In an attempt to create conditions for sustainable water management in a particular region (or more generally, within a certain system), a variety of counter-measures is possible. With regards to the production of agricultural raw products, reducing evaporation, improving water storage, and alleviating water runoff from the system can be noted as measures of particular relevance, unless the required minimum of water runoff has already been reached. There are many options to influence evaporation or evapotranspiration, e.g. by cultivating crops under glass or foil or by choosing a certain type of irrigation, a certain type of crop or different types of soil cultivation. Another possible option could be the cultivation of new types of crops that help to decrease evapotranspiration. The effective storage of water will ensure that no more water than necessary will flow out from the region in times of high precipitation. This should ensure that enough water will be available during periods of drought. Especially in developing countries, the concept of Integrated Water Resources Management (IWRM) mentioned in section 6.3 constitutes one potential option for organising and coordinating effective counter-measures.

Apart from the storage of water, raw materials for food should also be stored both regionally and globally in order to allow for a balancing of fluctuations in harvest yields and prices and in order to be prepared for crisis situations. As illustrated in section 5.1, the global storage of cereals alone equals to a volume of 500 km^3 of virtual water. It was already suggested that raw food materials and not water should be stored (Renault, 2003). In this case, however, we have to bear in mind that high storage losses – caused especially by pest infestation or spoilage – may occur.

A substantial reduction in the cultivation of renewable raw materials (especially energy crops) in favour of a cultivation of plants intended for human nutrition would constitute a highly effective measure to ensure a sufficient provision of raw food materials without unsustainable water utilisation. The utilisation of waste from agricultural production of primary products or from food production for generating appropriate energy carriers is also an option worth supporting. The cultivation of energy crops as an alternative to the cultivation of plants used for the production of foodstuff should be reconsidered – and at least not subsidised – in light of the facts and arguments put forward in this work.

Imposing a cost-covering water price (as discussed in section 6.3) would serve as a useful incentive for the more efficient use of scarce water resources. As already mentioned, however, the global implementation of such a concept for the agricultural sector remains a distant possibility.

7.2 CONSEQUENCES AND RECOMMENDATIONS FOR THE BERLIN-BRANDENBURG REGION

According to various regional models, we can expect a marked increase in temperature for the region in the coming years. Moreover, precipitation can be expected to decrease in summer, while it is likely to increase in winter (though this projection is not a certainty) (cf. Lischeid, 2010). Even though it is still not possible to make accurate forecasts about how exactly climate change will affect evaporation and evapotranspiration on the whole (Köstner and Kuhnert, 2011), it is possible that water resources will become a scarce commodity at least during the summer months. Lischeid (2010) and Grünewald (2010) have recently published extensive work on the impacts of climate change on the landscape's water balance and the water balance in the Berlin Brandenburg region, as well as on the discussions on adaptation measures and challenges related to a sustainable use of water.

With regard to virtual water, it is not impossible that the (currently insignificant) amount of artificial irrigation will increase in the region. This would imply that more water will evaporate and thus will be withdrawn from the region. In the future, we should therefore check if, and to what extent, the water required for irrigation has been withdrawn from the region in a sustainable fashion. If more water is withdrawn than is added, the concept of unsustainable water (as suggested here) will be of use. The data required for the application of the modified concept in the Berlin Brandenburg region should be made available as soon as possible.

In the face of the facts and arguments presented in section 7.1 it can be expected that during the next decades the overall global climate change will have stronger impacts on agriculture in the Berlin Brandenburg region than regional changes in climate. Departing from the projected global scarcity of foodstuff (and thus agricultural raw products) that arises from the water scarcity observable in many regions of the world, the following tendencies and recommendations emerge:

Prices for agricultural raw products will rise. Producing these goods will, however, remain essential for the region despite the fact that precipitation is low by German standards and will therefore gain in importance.

With respect to an anticipated global scarcity of foodstuffs, we ought to reconsider the extensive cultivation of energy crops.

If water becomes an increasingly scarce resource, the quality of cultivated agricultural goods should be as high as possible in order to keep proportionate costs for water low. As explained earlier (Schubert, 2007), in this respect the federal state Brandenburg offers favourable conditions with regard to the supply of the Berlin metropolitan area.

An increased self-sufficiency (for example with regards to fresh fruit and vegetables) reduces the amount of imported virtual water and, in consequence, also the water footprint in other regions. According to the concept suggested here, however, only the amount of virtual water withdrawn from the exporting region in an unsustainable way should be considered, as it is solely this share that does harm to the exporting country. The data required for these imported goods have to be ascertained.

Efforts towards achieving sustainable water management in the region should be carried forward in the light of global change, and water pollution from agriculture (caused by applied fertilisers and plant protection products) needs to be constantly observed. In terms of virtual water, the goal remains to avoid using any water for production or service provision that has been withdrawn from a region in an unsustainable manner. Apart from water pollution, only this share of virtual water is to be considered harmful to the respective region, and should be avoided on these grounds. The concept suggested here identifies goods whose production was based on such an unsustainable withdrawal of water from the region and as such quantifies these products' unsustainable share of virtual water.

8. OUTLOOK

The virtual water concept proposed here and the water footprint concept derived from it, represent modifications and extensions of the existing concept. Of all the water required for the production of goods or the provision of services, the modified concept only considers the share of water that has been withdrawn from a region (or more generally a control volume) in an unsustainable way and as such may be harmful for this region. The concept therefore does not take into account "green" water, which stems from renewable precipitation and constitutes the lion's share of water used for the production of agricultural goods. The same applies to water that has been sustainably withdrawn from groundwater or other water resources. In other words, the concept presented here only considers "blue" water that has been unsustainably withdrawn and, in consequence, will be detrimental to the respective region in the long run.

Assessing whether water management is sustainable is rarely straightforward. In many cases it is, however, easier to decide whether water is utilised in an unsustainable way. Several examples for this can be found in the literature, such as a substantial annual reduction in the groundwater level for some regions or the drying-up of waters due to intensive artificial irrigation in agriculture (cf. Boßler and Strobel, 2009). As a first step, it appears appropriate to confine the focus to the clear-cut cases of unsustainable water management in agriculture. According to the previous concept, about 70% of virtual water relate to agricultural products. It is therefore justified if we confine ourselves to the agricultural sector.

For the clear-cut cases mentioned, it should be possible to collect the data required according to the proposed concept and to provide these data to the public. For such purposes, existing international and national institutions have already successfully provided data with respect to the existing concept of virtual water and thus can provide all the necessary prerequisites. It would be useful if an institution from Germany also participated in this production of data.

Such data, which could not be provided using the existing concept of virtual water, are useful for producers and exporting countries as well as for consumers and importing countries. Producers and exporting countries will find out if any (and if so, how much) virtual water originates from unsustainable utilisation. By this means, they would have a sound way of initiating suitable countermeasures. In turn, consumers and importing countries would receive reasonable data that would allow them to decide as to whether (and to what extent) they want to participate in an unsustainable utilisation of other regions' water resources by purchasing certain goods. On the whole, the extended concept of virtual water suggested here aims to provide a comprehensible database that can contribute to a more sustainable use of water resources.

It should be noted that according to the concept outlined here, the virtual water content of many products can be expected to be lower (by a factor of more than 10) than previously assumed and could even be completely irrelevant in the cases of some products. Once the volumes of water required for the production of goods or the provision of services is calculated using the modified concept, it is safe to say that the resulting values will be much smaller – and thus also much less spectacular – than initially expected. Nonetheless, these data should be provided at least as additional pieces of information in order to be able to openly confront the misinterpretations mentioned in section 5.2.

However, questions concerning water quality and water pollution have not yet been fully and satisfactorily clarified in the concepts of virtual water and water footprint. As was shown in section 4.3, the introduction of the concept of "grey" water according to the definition of Hoekstra has been unsatisfactory. Further research is therefore required to improve the overall concept so as to allow for a more sustainable utilisation of existing water resources.

9. ABBREVIATIONS AND DIMENSIONS

cap	capita
c_{dis}	molar concentration of the dissolved solids in water
E	evaporation
ET	evapotranspiration
ETC	evapotranspiration coefficient
ha	hectare (10,000 m^2)
km^3	10^9 m^3
LCA	life cycle assessment
P	mass of precipitation within a balance scope (control volume)
p_{cap}	capillary pressure
R	mass of water runoff from a balance scope (control volume)
ΔS	changes in stored mass of water in a balance scope (positive when stored mass increases)
T	transpiration
V	mass of evaporated water from a balance scope (control volume)
v	virtual water content, e.g. specified in litres of water/kg product
v_b	"blue" virtual-water content (litres of water/kg product)
v_g	"green" virtual-water content (litres of water/kg product)
v_{grey}	"grey" virtual-water content (litres of water/kg product)
v_{tot}	total virtual-water content (litres of water/kg product)
WF	total water footprint
WF_b	"blue" water footprint
WF_g	"green" water footprint
WF_{grey}	"grey" water footprint
yr	year
Z	mass of water inflow into the considered region (control volume) within a balance scope

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