

Water-use and impact-weighted water footprints – methodological approach and case study for two Austrian milk production systems

Stefan J. Hörtenhuber^{1,2,*}, Rainer Weißhaidinger¹, Thomas Lindenthal^{1,3}, Werner J. Zollitsch²

¹ Research Institute of Organic Agriculture (FiBL) Austria

² BOKU - University of Natural Resources and Life Sciences Vienna, Department of Sustainable Agricultural Systems

³ BOKU - University of Natural Resources and Life Sciences Vienna, Centre for Global Change and Sustainability

* Corresponding author. E-mail: stefan.hoertenhuber@fibl.org

ABSTRACT

Freshwater is a scarce resource in many parts of the world. Besides the quantitative restriction, a potential contamination of water resources ranks high on the agenda of environmental concerns in many regions. The objective of this paper is to describe methods for impact-weighted grey water footprints (WFs), derived from grey water-use (WU) estimates. Furthermore, total WU (blue surface- and groundwater, green evapotranspiration water from precipitation and virtual grey dilution water) and WFs (impact-weighted blue and grey water footprints) are calculated based on life cycle assessment (LCA) principles for two Austrian milk production systems (PS). We identified two approaches for impact-weighted grey water results: (1) a regional catchment area-based approach and (2) a local approach. It is shown for the milk PS that differences in management result in different virtual grey WU with high importance for the overall water demand. Analogously management- and precipitation-related impact-weighted grey WFs completely dominate the overall WF results.

Keywords: water-use, water footprint, nitrate emissions, grey water, impact-weighting

1. Introduction

Freshwater is a scarce resource in many parts of the world. Besides the quantitative restriction, a potential contamination of water resources ranks high on the agenda of environmental concerns in many regions. In recent years, scientific studies have started to analyze factors influencing water-use (WU), the resulting impact on water-resources and water quality induced by diverse production systems and management strategies for comparable food products. Earlier studies on amounts of “virtual water” (see e.g. Allan et al. 2003) or on different types of so-called “water footprints” (WFs; see e.g. Hoekstra et al. 2011) implemented methodologies with lower resolution to analyze and illustrate hydrological aspects in a broader context: the concepts were primarily developed to show effects of WU in all stages of supply chains for nations, companies or products and to illustrate virtual global water flow.

Previous studies focused on food production’s water consumption only, but did not or not fully account for the effects of production on water quality. From these it was often concluded that high-output production results in a lower water demand per unit of product output. Contrarily, a few recent studies using refined methodology demonstrate effects of different production systems on water aspects with a focus on water quality and grey water (i.e. virtual water demand to dilute the main emitted pollutant in a specific water body) on a product level: For example, Ercin et al. (2012) compared soy production from different countries and diverse production methods and found that shifting from non-organic to organic farming may reduce the grey water related to soybean cultivation by 98%. Franke and Mathews (2013) found that organic farming practices for Indian cotton showed a five times smaller grey water demand than for conventional production, while having comparable land productivities as in conventional farming. However, these concepts are based on WU at an inventory level, but the water demand is not weighted by its impact on a water system which could influence a regional or local WF result. In contrast to a global warming potential (carbon footprint), which provides a measure for an impact on global warming with globally equal impact factors for the different greenhouse gases, impacts of WU vary spatially and temporally and because of the related methodological difficulties, they are hardly incorporated in WF studies. Opposed to the unweighted WU, a few impact assessment methods were created in recent years, e.g. the water stress index (WSI; Pfister et al. 2009). The latter was developed for blue water (ground- and surface-water used) only and characterizes the impact relevance of regional water consumption (for midpoint modelling). Regionally varying stress indicators are used, ranging from 0 (no water stress) to 1 (extreme water stress) for more than 11'000 globally differentiated watersheds in order to calculate product water footprints.

The objectives of this paper are: (1) to propose a method that is based on life cycle assessment (LCA) principles and LCA data and fully accounts for all kinds of WU (blue, green and grey water) and also for impact-

weighted WFs (red and impact-weighted grey water); (2) to describe characterization methods which address impact-weighted grey WFs. (3) Furthermore, to demonstrate the implementation of this method, WU results (for blue, green and grey water) and WFs (red and impact-weighted grey water) are calculated per kg milk for two typical different Austrian milk PS.

2. Methods

2.1. Proposed method, scope and system boundaries

This contribution presents a method for water-use (WU) and water footprint (WF) estimates for agricultural products, which is based on LCA principles and accounts for all relevant life cycle-related inputs for the inventory level. This includes: (1) blue water, i.e. surface or groundwater used during production processes (e.g. in housing or for irrigation); (2) green precipitation water which is evapotranspired by plants and soil; (3) grey water, i.e. the amount of water needed to dilute contaminants in affected freshwater. For the impact-weighted water footprints, the proposed method covers the so-called red WF, i.e. an impact-weighted blue WF, (see e.g. Pfister et al. 2009) and introduces an impact-weighting for grey water, which has not been covered in previous contributions (see e.g. Launiainen et al. 2014, Chenoweth et al. 2013). Deriving red water through a weighting step for blue water is meant to taking into account the regional stress on freshwater resources that is related to a WU. In analogy, grey WU results are impact-weighted in order to represent the water quality stress: any contamination of water not only leads to an increase in the grey WU of a product, but exerts a particular impact if an affected water body's quality is already impaired, increasing the amount of water needed to dilute the contaminant to acceptable contents. The NO_3 -contamination of groundwater related to agricultural production may serve as an example for this: The NO_3 -content in water bodies is mainly affected by the amount of precipitation water and flowing water for groundwater and surface water bodies, respectively. Additionally, it is influenced by the amount of NO_3 -N emitted into the water systems, depending on the cultivation management and on further NO_3 -loads e.g. from deposition. The proposed impact-weighting does not only account for the specific grey water demand of an assessed product, but also includes the effect of regional NO_3 -loads on groundwater. The impact-weighting factor depends on the groundwater NO_3 -content, which is assumed to be influenced by long-term cultivation management and related NO_3 -loads. For the local approach, constant long-term conditions are assumed, which are reflected in the current state of the respective water bodies.

Green water, which is included at the inventory level (WU method), is not considered for the impact-weighted level (WF method) any more. This green water is not comparable to blue water, as it is assumed not to contribute to water scarcity from a water management perspective, and its impact is related to the indicator land use (Ridoutt and Pfister 2010). Contrarily, other authors argue that green water is also limited, can be substituted by blue water and may affect blue water availability (Jefferies et al. 2012, Berger and Finkbeiner 2012, in: Chenoweth et al. 2013); consequently, we include green water on the inventory level.

Figure 1 illustrates water types according to different methods and results included in this paper for WU (inventory level) and for WFs (impact level), i.e. red water according to Pfister et al. (2009) and an impact-weighted grey water footprint affected by the background concentration of the substance to be considered (here: nitrate).

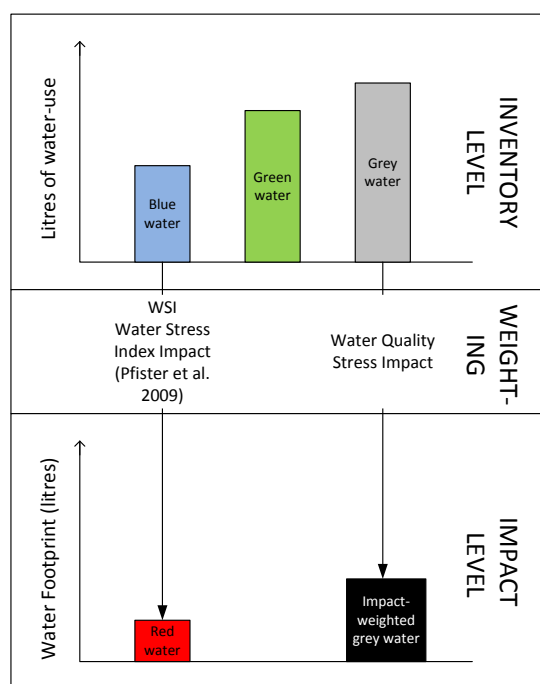


Figure 1: Water types covered in our method for water-use estimates and a product water footprint.

The concept of WU is based on Hoekstra et al. (2011) concerning blue, green and grey water but uses other data sources and calculation procedures for quantification. Table 1 gives an overview of the calculation procedures and of some of the algorithms provided in this paper for WU and WF calculations at different stages in the life cycle for the case of milk production. System boundaries were defined to include the most important processes requiring water, such as the supply of input factors relevant for the production of feedstuffs, evapotranspiration of plant feedstuffs, water directly used for livestock husbandry and for milk processing in the dairy (Table 1). Generally, WU (water demand) is calculated as the product of activity data (e.g. amounts of mineral nitrogen fertilizers to produce one unit of feedstuff) and water demand factors per unit (e.g. liters (L) of blue water needed per kg nitrogen fertilizer produced). While some WU estimates such as for blue drinking and cleaning water used in housing represent gross water demands, the red WF results describe further weighted net losses of water from a local system (e.g. irrigation water lost by evapotranspiration or water contained in products leaving the local system). Grey water is generally not lost from a local system, but is a virtual water demand which is accounted for in the water balance to include effects of water pollution on water demands.

Table 1: Different water types and algorithms provided for water-use and water footprints for different elements of a milk production system.

	Water types covered at inventory level	Equation	Water types covered at impact level	Equation
Cultivation of feedstuffs	Blue _{irrigation}	1	Red _{irrigation}	2
	Green _{evapotranspiration}	3		
	Grey _{leaching}	4	Impact-weighted grey _{leaching}	5 / 6
Production of mineral fertilizers/pesticides	Grey _{energy-use}		Impact-weighted grey _{energy-use}	
	Blue _{fertiliser-processing}		Red _{fertiliser-processing}	
Industrial processes for feed production and in the dairy	Grey _{energy-use}		Impact-weighted grey _{energy-use}	
	Blue _{feed-processing}		Red _{feed-processing}	
Livestock husbandry	Grey _{energy-use}		Impact-weighted grey _{energy-use}	
	Blue _{housing}		Red _{housing}	
Transports (between & within all elements) and trade	Grey _{energy-use}		Impact-weighted grey _{energy-use}	
	Blue _{cleaning}		Red _{cleaning}	
Dairy processing	Grey _{energy-use}		Impact-weighted grey _{energy-use}	
	Blue _{processing}		Red _{processing}	
	Blue _{cleaning}		Red _{cleaning}	
	Grey _{energy-use} (Grey _{wastewater})		Impact-weighted grey _{energy-use} (Impact-weighted grey _{wastewater})	

2.2. Blue water use for irrigation – methodological aspects and input data

For cultivation of feedstuffs, regionally varying amounts of blue water have to be used for irrigation ($Blue_{irrigation}$) to compensate for a lack of precipitation. Equation 1 [Eq.1] quantitatively describes this WU (liters of blue water for irrigation per kg milk).

$$Blue_{irrigation} = \sum_{i=1}^n Feed_{i,r,m} * I_{i,r,m} = \sum_i^n Feed_{i,r,m} * irr_{i,r,m} * ET_{i,r,m} \quad Eq.1$$

where $Feed_{i,r,m}$ is the amount of different feedstuffs i from specific regions r , produced with management practices m to yield one unit (kg) of milk, multiplied with the feedstuffs' specific irrigation water demands $I_{i,r,m}$ (specific for feedstuffs/crops i , for regions r and for management practices m ; in $L \text{ kg}^{-1} \text{ DM}$). $ET_{i,r,m}$ describes the evapotranspiration water demand (in L) for selected Austrian feedstuffs i as derived from the EPIC model (Schmid 2011, Asamer et al. 2011; see Table 2). The term $\%irr_{i,r,m}$ represents the proportion of irrigation water from overall water for ET plus recharge water amounts for crop i in region r for management practices m . Due to mostly sufficient precipitation for evapotranspiration, blue water is commonly not used for irrigation feedstuff production in Austria, where only a small proportion of cropland is irrigated. Most feed producers do not have the infrastructure for irrigation. Consequently, a proportion ($\%irr_{i,r,m}$) of only 1 % and 2 % of overall evapotranspiration water $ET_{i,r,m}$ was estimated for Austrian grain and corn production, respectively. Siebert and Döll (2010) show a comparable percentage of blue water from overall virtual water for crops from other regions which mainly export crops to Austria. Hence, we assumed the same values for $\%irr_{i,r,m}$ for imported cereal grains, maize and soybeans.

We used mass allocation for co-products, e.g. 1 kg of soybean cake shows an equal evapotranspiration water demand as toasted soybeans or extracted soybean meal (see Table 2).

Table 2: Water required for evapotranspiration for selected concentrate feedstuffs (liters per kg DM).

Feedstuff	$ET_{i,r,m=Austria}$	Feedstuff	$ET_{i,r,m=Austria}$
	$m = \text{Organic} / \text{Conventional}$		$m = \text{Organic} / \text{Conventional}$
Triticale & wheat	471.5 / 480.8	Lucerne meal	502.0 / 528.7
Barley	467.4 / 490.9	Wheat bran	471.5 / 480.8
Maize (corn)	505.7 / 544.9	Soybean cake	477.5 / 495.1
Peas	455.2 / 448.6	Extracted soybean meal	477.5 / 495.1

2.3. Irrigation-related red water footprint

For characterizing the irrigation-related water footprint, we applied the Water Stress Index WSI (Pfister et al. 2009) to our inventory results $Blue_{irrigation}$ for the feedstuffs $Feed_{i,r,m}$. We assumed that all feedstuffs for the milk production were cultivated in Austria or in the neighboring countries (Hungary, Slovakia, Slovenia) and Croatia or Romania, which all belong to the water catchment basin of the Danube. Hence we multiplied all blue water results from the inventory level with a WSI-factor (WSI_r) of 0.0689 for this water catchment basin according to Pfister et al. (2009). As an exemption, imported soybeans for extracted soybean meal are assumed to be imported mainly from Brazil, Argentina and USA; on average, we assumed a WSI-factor of 0.012 for imported soybeans (Pfister et al. 2009). See equation 2 to for the detailed calculation:

$$Red_{irrigation} = Blue_{irrigation} * WSI_r = \sum_{i=1}^n Feed_{i,r,m} * I_{i,r,m} * WSI_r \quad Eq.2$$

2.4. Green water (precipitation) use – methodological aspects and input data

Green water was estimated at the inventory level as the difference between the overall water demand for evapotranspiration as derived from the EPIC model and the amount of irrigation water. Equation 3 describes this green water demand from precipitation which results from evapotranspiration and is usually removed from local water cycles. With the proposed method green water is accounted for at the inventory level; it is also limited and can be substituted by blue water. Additionally, we estimated a yield-related loss of green water from reduced

precipitation in the case of preceding clearing of tropical forests (based on data from Avissar and Werth 2005). This loss of green water from a regional water cycle is relevant for a part of soybeans from South America.

$$Green_{evapotranspiration} = \sum_{i=1}^n Feed_{i,r,m} * (ET_{i,r,m} - I_{i,r,m}) = \sum_{i=1}^n Feed_{i,r,m} * (ET_{i,r,m} * (1 - \%irr_{i,r,m}))$$

Eq.3

2.5. From grey water-use to the impact-weighted grey water footprint

The concept of grey water related to crop cultivation is based on Hoekstra et al. (2011) but was refined: First we confirmed nitrate to be the most relevant substance in terms of limiting ground water quality for most of Austria (Austrian Environment Agency 2007). Furthermore, we changed the constant 10 % nitrogen (N) assumed by Hoekstra et al. (2011) to be leached as nitrate to proportions for average conventional production, which were found in a meta-analysis covering 127 studies (Kolbe 2002). As a result of the meta-analysis, 26.6 % and 11.0 % of applied N for conventional management were calculated to be lost as nitrate from arable land and permanent grassland, respectively. The parameter $\%leaching_{i,r,m}$ in equation 4 represents the proportion of lost NO_3-N in connection to $N_{applied\ i,r,m}$, i.e. the amount of N applied per kg of feed from fertilizers including available N from biological N-fixation and deposition of gaseous N-losses from livestock husbandry (see Hörtenhuber et al. 2010 and Hörtenhuber et al. 2011 for activity data on N loads and N applied as well as N-emissions for selected feedstuffs). As the term $(N_{applied\ i,r,m} * \%leaching_{i,r,m})$ is given in kg NO_3-N , it has to be converted into NO_3 (nitrate) by division (0.2259).

In contrast to previous literature sources, this contribution does not include a “regional background concentration” of nitrate in affected water bodies for calculation of grey water. Hence, for “Grey_{leaching}” per kg milk, i.e. the amount of virtual grey water which is needed to dilute pollutants in fresh water, we used a maximum tolerable limit for drinking water quality ($C_{max\ NO_3}$) of 45 mg (0.000045 kg) $NO_3\ L^{-1}$.

$$Grey_{leaching} = \sum_{i=1}^n Feed_{i,r,m} * \left(\frac{N_{applied\ i,r,m} * \%leaching_{i,r,m}}{0.2259 * max_nitrate\ drinking\ water} \right)$$

Eq.4

Figure 2 describes all parameters and processes covered in the proposed method for estimation of WU at the inventory level (green, blue and grey water; the latter based on NO_3-N) for the cultivation of feedstuffs.

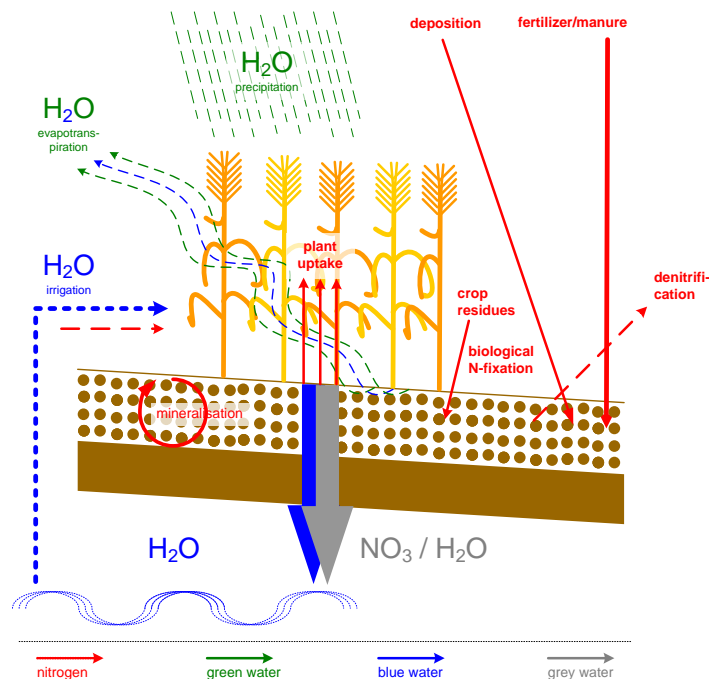


Figure 2: Parameters covered in the proposed method for estimation of water-use concerning cultivation of feedstuffs.

Relatively small amounts of virtual grey dilution water result from potentially leached N related to energy consumption that is primarily emitted as NO_x-N, NH₃-N or N₂O-N from cultivation of feedstuffs, animal husbandry, transports or dairy processing, and is termed Grey_{energy-use} herein. The amount of leached N is based on the source of energy, i.e. on its specific N emission. According to an IPCC (2006) default value, we assumed 30 % of all gaseous N-emissions from energy supply and usage to be lost to water bodies via deposition on natural land, on settlements without water treatment in sewage plants or on agricultural land, followed by leaching.

As this energy-related grey water is no key source for the overall water demand, a simplified calculation may be used: we converted total energy needed for feed processing, housing, milking, milk-cooling and processes in the dairies, etc. (see Table 1) into diesel-equivalents and calculated the associated CO₂-eq emissions. Based on Hausberger (2000), assumptions concerning NO_x-N, NH₃-N or N₂O-N emissions and the 30 % leached N (IPCC 2006), we calculated 77.3 L of grey dilution water per 1 kg of CO₂-eq from fossil fuels.

The impact-weighted grey water footprint is calculated from a combination of the cultivation-related Grey_{leaching} water demand and the less relevant Grey_{energy-use} water demand plus a weighting factor to account for a regionally variable “water quality stress”.

Two different approaches may be used to derive an impact-weighted grey WF (“Imp.Grey” in equations 5 and 6):

(1) In a regional (catchment based) approach, the ratio between the regional concentration of the substance that defines the grey water (here: nitrate; $C_{regional\ NO_3}$ in mg NO₃ L⁻¹) and its maximum tolerable concentration in drinking water ($C_{max\ NO_3}$, 45 mg L⁻¹) characterize the regional “water quality stress” and is used as an impact factor.

$$Imp. Grey_{leaching-approach(1)} = (Grey_{leaching} + Grey_{energy-use}) * \left(\frac{C_{regional\ NO_3}}{C_{max\ NO_3}} \right) \quad Eq.5$$

(2) For a local approach, the impact-weighted grey WF is derived by using the ratio of grey water needed for dilution of emitted nitrate and the water actually available for dilution as an impact factor. The water available for dilution results from water recharge amounts as a function of local annual precipitation plus irrigation minus evapotranspiration (each per kg of crop).

$$Imp. Grey_{leaching-approach(2)} = (Grey_{leaching} + Grey_{energy-use}) * \left(\frac{Grey_{leaching} + Grey_{energy-use}}{\frac{(\sum_{i=1}^n Feed_{i,r,m} * (pre_r + I_{i,r,m} - ET_{i,r,m}))}{\sum_{i=1}^n Feed_{i,r,m}}} \right) \quad Eq.6$$

where pre_r is defined as the local precipitation (Green_{evapotranspiration} water plus green water for ground- and surface water recharge) in L per kg harvested yield.

For approach (1) the average impact factors for derivation of the impact-weighted grey WF are 0.336 and 0.334 for the two production systems (PS) “PS A” and “PS L”, respectively (see subsection 2.7 for further details on the PS). The associated average values for $C_{regional\ NO_3}$ in drinking water are approximately 10 mg for grassland areas and 25 mg for arable land (BMLFUW/UBA 2006, 2010). For approach (2), we obtain an average impact factor of 1.1928 for PS A with differing recharge water amounts for on-farm areas and land used to produce bought-in concentrates. For PS L we calculated an average impact factor of 1.5268.

2.6. Further sources for blue and red water demand

In addition to blue (and red) water used for irrigation, livestock husbandry requires some blue water consumed by the animals and for cleaning purposes. The drinking water demand of dairy cows and heifers was calculated based on their diets (Wiedner 2010). Average default values from literature (KTBL 2008) were assumed for the required quantity of cleaning and flushing water. Furthermore, some blue water is needed for cleaning purposes in feed processing plants, for cleaning of transport facilities and especially in the dairies

(Nielsen 2003, Theilen and Goldbach 2000). For the red WF, i.e. the impact-weighted blue water demand as described above (subsection 2.1), see the Water Stress Index WSI (Pfister et al. 2009) and subsection 2.3 for further details.

2.7. Input data for Austrian milk production systems and their upstream supply chains

Amounts of feed used to produce one kg of energy-corrected milk were taken from Hörtenhuber et al. (2010) for an alpine and a lowland milk production system (PS “A” and PS “L”). The assessment includes on-farm land and land areas indirectly claimed via bought-in concentrates. Including the effects of the rearing phase and accounting for the by-product beef from cull cows, dairy cows need 0.87 and 0.62 kg DM roughage, mostly from permanent grassland, per kg of energy-corrected milk for PS A and PS L, respectively; an additional 0.16 and 0.18 kg DM of concentrates are fed per kg of milk in PS A and PS L, respectively. The concentrate mixtures are mainly based on barley, wheat and corn as well as some supplementary protein from rapeseed cake, extracted soybean meal and distillers dried grains with solubles; for further details see Hörtenhuber et al. (2010).

Concerning inputs into milk PS as well as their upstream supply chains and calculation procedures described in subsection 2.5, a total of 12.9 L (34 % from fertilizer production) and 13.2 L (20 % from fertilizer production) of Grey_{energy-use} dilution water demand were calculated for PS A and PS L, respectively. These result from energy consumed for cultivation and processing of feedstuffs, from the production of mineral fertilizers and pesticides, including gaseous N-losses from the fertilizer production (see Table 1), for livestock husbandry and upstream transports.

3. Results

The average sum of unweighted WUs for PS A and PS L is around 700 L per kg milk, with an average grey WU of 314 L/kg (45% of total WUs). In detail, we found 266 and 361 L of grey dilution water per kg milk for PS A and PS L, respectively. Green WU for cultivation of feed was 384 and 304 L/kg of milk for PS A and PS L, respectively; green water lost from the regional cycle due to deforestation added up to 16 (PS A) and 17 (PS L) L/kg. Blue water for irrigation (grains and corn) was identified to be 4 L per kg milk for both PS A and PS L. In total, blue WU estimates for housing, for production of mineral fertilizers and for dairy processing purposes resulted in 13 L/kg (similarly for both PS A and PS L; about each 5 L for housing and the dairy, the other 3 L for production of mineral fertilizers and pesticides). Equally, additional 13 L per kg milk were found for both PS A and PS L for grey water from livestock husbandry's or transports' energy demand-related deposited and leached N-emissions. The latter 13 L are accounted for in the category “Grey water for crops and roughage cultivation” in Figure 3, as they are assumed to be deposited mainly on the agricultural land.

The blue and green WU is usually connected to the production efficiency and is therefore higher for the alpine (+25 %) than for the lowland PS, whereas the latter shows greater grey WU (+33 %), especially due to higher nitrate emissions related to the greater proportion of arable land used (see Figure 3). Comparably, the impact-weighted grey WF is also smaller for PS A than for PS L; the difference between the two PS is 32% following approach (1), which reflects a regional perspective, and 72% if estimated by approach (2), which represents the local scale.

In contrast to the impact-weighted grey WF, red water is of very little relevance for Austrian dairy production, because only small amounts of blue water are required, which partially do not leave the local systems and are not scarce in the regions addressed (Pfister et al. 2009). Consequently, red water (less than 1 L per kg milk) is hardly visible in Figure 3.

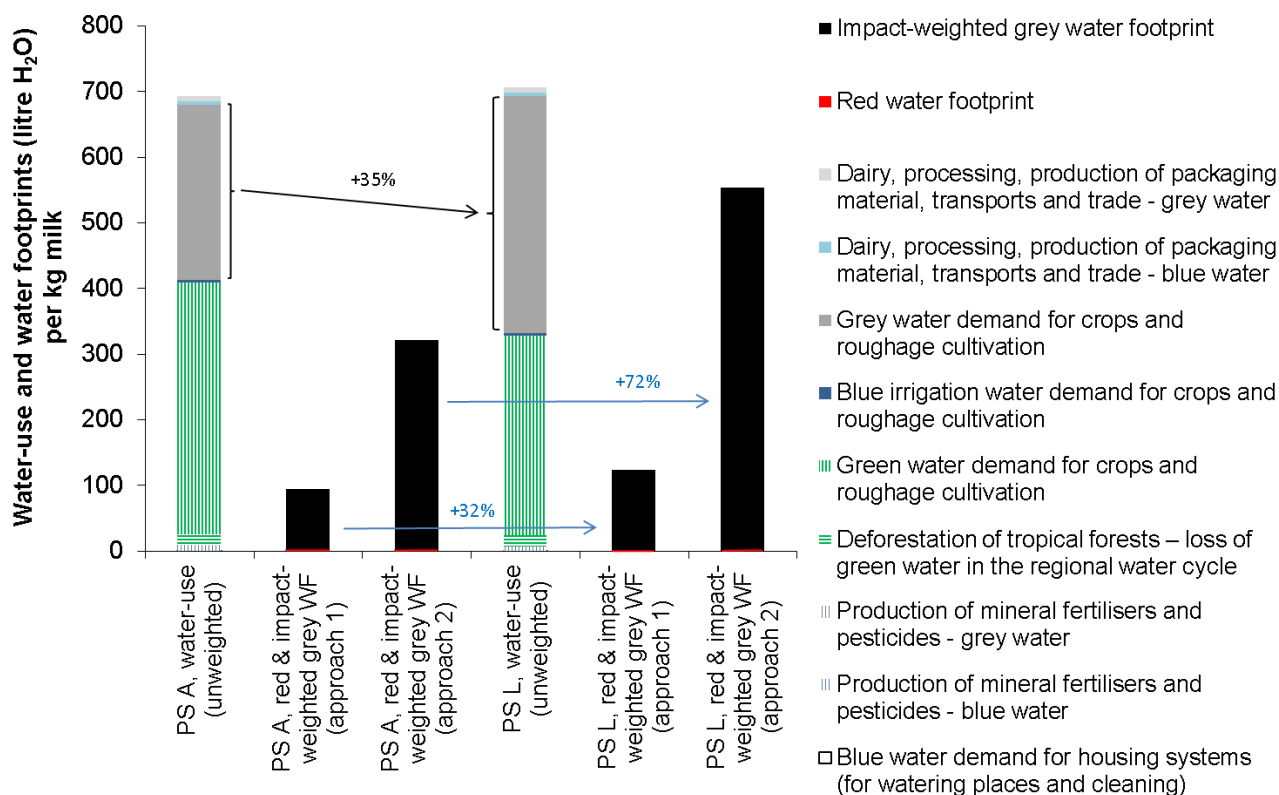


Figure 3: Water-use (blue, green and grey water) and the impact-weighted grey water footprint as well as red water for two dairy production systems in Austria (alpine PS A and lowland PS L).

4. Discussion

Both impact-weighting approaches (1) and (2) seem to be practicable for the impact-weighted grey WFs of typical crops. For specific crops (e.g. with a high proportion of N lost as NO₃) or for a small-structured agricultural area with crop rotations (within one catchment area), we propose to use the less detailed regional approach (1). As a consequence of the less specific influences, approach (1) results in less diverging WF results than approach (2). In approach (2) the impact factor is derived from processes in the upper soil layer of a cultivated area only, but does not account for the dilution effect of water transfer from areas with less or no N fertilization such as forests. Deviating therefrom, the impact factor is derived from a concentration of the relevant substance in affected water sheds in approach (1), which therefore better represents the regional situation, particularly in terms of agricultural impacts (e.g. nitrate losses).

Some conceptual aspects are currently discussed in the relevant literature (see Chenoweth et al. 2013): (i) Should different types of water be added up for a final quantification? While blue and green water represent physically used amounts of water, grey water is a virtual water-use, which is not accompanied by a physical water consumption. Consequently, we did not compare total WU per kg of liquid milk, but compared single sources for water demand. (ii) Green water is naturally supplied by precipitation and thus it is questionable whether it is to be accounted for in a WF, which is assumed to consist only of human-driven water demands in some concepts. Contrarily, we assume green water to have an important impact on available amounts of blue water (in downstream water bodies) and also an impact on grey water, as it dilutes nutrient or pollutant loads. As a consequence, the proposed method accounts for green water at the inventory WU level and estimates an impact-weighted grey WF. This grey WF is influenced by the green water-use, mainly through its function for recharging water bodies. (iii) Most water footprints which implement grey water derive its demand from nitrogen losses, although in many areas other substances may be most limiting for the water quality. Therefore, attention must be given to a proper estimation of the grey water use and to the identification of the substance most critical to water quality, which ultimately defines the grey water demand.

Grey water is not considered in typical multiple-indicator LCA studies, as they usually cover nutrient (nitrogen and phosphorus) loads in an eutrophication potential and partially also pollutant loads (mainly pesticides) in toxicity indicators. To avoid double counting, these studies use at the most blue or red water as an indicator of resource use – if at all. Contrarily, grey water estimates may provide an important information in studies which do not integrate eutrophication potential estimations or toxicity indicators, which not only aim at scientific analysis, but also at the communication of environmental concerns. Regarding the understanding and interpretation of qualitative and quantitative aspects of water resources, the concepts of virtual water and water footprints already provided some knowledge (see Chenoweth et al. 2013). However, in contrast to an eutrophication or a toxicity potential, the impact-weighted grey WF described in this paper even shows an advantage from a scientific perspective: this indicator includes a regionally or locally variable impact of emissions by addressing the background concentration of the substance concerned, such as nitrate, phosphorus or different pesticides.

The method suggested herein basically follows life cycle assessment principles (see guidelines for life cycle assessments: e.g. ISO 2006, BSI 2011) which makes it coherent to other LCA criteria and allows for an integration into a wider assessment, whenever the use of water resources is of interest.

5. Conclusion

We propose an integral consideration of quantitative and qualitative aspects related to water resources in so-called “water footprints”, following principles of life cycle assessment. Blue, green and grey water-use shall be assessed at the inventory level and shall be amended by considering red water and an impact-weighted grey water footprint. The latter is defined within the proposed method to characterize the impact of a grey water demand in accordance with an existing method for red water.

For the overall water-use of the two production systems presented herein, an inclusion of grey water leads to a disadvantage for the more intensive PS L as compared to PS A. Similarly, the consideration of the regional and local impact for a WF according to the suggested approaches (1) and (2) leads to a disadvantage for the more intensive PS L due to a substantially higher virtual impact-weighted grey WF.

However, for crops and crop rotations with an inherent risk for water pollution we propose to use the less detailed impact-weighting approach (1), which should be based on measured data, focuses on the regional level and better reflects conditions for small-structured agriculture and the impact of nitrate leaching on regional water quality.

6. References

- Allan J A (2003) Virtual water – the water, food, and trade nexus: Useful concept or misleading metaphor? *Water International* 28 (1), pp 106-113.
- Asamer V, Stürmer B, Strauss F, Schmid E (2011) Integrierte Analyse einer großflächigen Pappelproduktion auf Ackerflächen in Österreich. In: Eder M., Pöchtrager S. (ed), *Jahrbuch der österreichischen Gesellschaft für Agrarökonomie* 19/2, 41-50 (in German).
- BMLFUW/UBA (Bundesministerium für Land-, Forstwirtschaft, Umwelt und Wasserwirtschaft / Umweltbundesamt; Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management / Environment Agency Austria, eds; 2006) *Wassergüte in Österreich – Jahresbericht 2006* (in German).
- BMLFUW/UBA (2010) *Wassergüte in Österreich – Jahresbericht 2010*. <http://www.umweltbundesamt.at/jb2010> (last accessed: 2014-04-13; in German).
- BSI (British Standardisation Institute; 2011) Publicly Available Specification PAS 2050 – Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. <http://www.bsigroup.com/upload/Standards%20&%20Publications/Energy/PAS2050.pdf> (accessed: 2014-04-06) ISBN 978 0 580 71382 8.
- Chenoweth J, Hadjikakou M, Zoumides C (2013) Quantifying the human impact on water resources: a critical review of the water footprint concept. *Hydrol. Earth Syst. Sci. Discuss.* 10, 9389-9433.
- Ercin A E, Aldaya M M, Hoekstra A Y (2012) The water footprint of soy milk and soy burger and equivalent animal products. *Ecological Indicators*, 18: 392–402.

- Franke N, Mathews R (2013) C&A's Water Footprint Strategy: Cotton Clothing Supply Chain. Corporate water footprint publication – Water Footprint Network. http://www.waterfootprint.org/Reports/CA_Strategy_Final_Report_Formatted%2006.08.2013.pdf (accessed: 2014-01-05).
- Hausberger S, Pischinger R (2000) Emissionen des Off-Road-Verkehrs im Bundesgebiet Österreich für die Bezugsjahre 1990 bis 1999. Studie im Auftrag des Umweltbundesamtes Österreich, Graz-Wien (in German).
- Hoekstra A Y, Chapagain A K, Aldaya M M, Mekonnen M M (2011) The water footprint assessment manual: Setting the global standard, Earthscan, London, UK. 203 pp. ISBN 978-1-84971-279-8.
- Hörtenhuber S, Lindenthal T, Amon B, Markut T, Kirner L, Zollitsch W (2010) Greenhouse gas emissions from selected Austrian dairy production systems: model calculations considering the effects of land use change. *Renewable Agriculture and Food Systems* 25 (4), 316-329.
- Hörtenhuber S, Lindenthal T, Schmid E (2011) Water Footprint – Ein Beitrag zur Nachhaltigkeitsbewertung am Beispiel der Milcherzeugung. In: ALVA (ed), Proceedings of the 66th ALVA Conference, May 23-24 2011, Graz, Austria, 87-89 (in German).
- IPCC (International Panel on Climate Change; 2006) Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. ed. by Eggleston H S, Buendia L, Miwa K, Ngara T, Tanabe K, Institute for Global Environmental Strategies (IGES), Kanagawa, Japan.
- ISO (2006) ISO 14040. International Standard: Environmental management – Life cycle assessment – Principles and framework. Second edition.
- Kolbe H (2002) Wasserbelastung in Abhängigkeit von der Landnutzung. *Ökologie & Landbau* 122(2), 34-35 (in German).
- KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft; German Association for Technology and Structures in Agriculture; 2008) Wasserversorgung in der Rinderhaltung. Wasserbedarf – Technik – Management. KTBL-Heft 81. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt, Germany (in German).
- Launiainen S, Futter M N, Ellison D, Clarke N, Finér L, Högbom L, Laurén A, Ring E (2014) Is the water footprint an appropriate tool for forestry and forest products: the Fennoscandian case. *AMBIO* 43, 244-256. doi: 10.1007/s13280-013-0380-z.
- Nielsen P H (2003) Soy meal. LCA-Database. <http://www.lcafood.dk> (accessed: 2014-01-05).
- Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. *Environ Sci Technol* 43(11), 4098-4104.
- Ridoutt B G, Pfister S (2010) A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environmental Change* 20, 113-120.
- Schmid E (2010) Water consumption of crops in Austria (unpublished calculations). BOKU – University of Natural Resources and Life Sciences Vienna, Institute for Sustainable Economic Development.
- Siebert S, Döll P (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology* 384, 198-217.
- Theilen U, Goldbach H (2000) *Umwelthandbuch Molkereien*. Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) und Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Eschborn, Germany (in German).
- Wiedner G (2010) Wasser als Futtermittel. http://www.lko.at/netautor/napro4/appl/na_professional/parse.php?id=2500%2C1525369%2C1520789%2C3997%2CaW5saW5lbW9kZT1wcmludA%3D%3D (accessed: 2014-01-05; in German).