Journal of Cleaner Production 73 (2014) 52–62

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production

Stephan Pfister [a,*], Peter Bayer [b]

[a] Ecological Systems Design, Institute of Environmental Engineering (IfU), ETH Zurich, 8093 Zürich, Switzerland
[b] Engineering Geology, Geological Institute, ETH Zurich, 8093 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 7 April 2013
Received in revised form
3 September 2013
Accepted 8 November 2013
Available online 22 November 2013

Keywords:
Water footprint
Agriculture
Blue water consumption
Temporal resolution
Global assessment
Life cycle assessment

ABSTRACT

Irrigation is the dominant human activity leading to water stress, with environmental consequences on the local and global level. The relevance of spatial resolution to the assessment of water consumption and to impacts related to crop production has been acknowledged in previous research on water footprint. The temporal aspects of crop cultivation and the related impacts, however, have been neglected in analyses with global coverage. Such aspects are important since different crop options can shift irrigation water consumption within a year, increasing or decreasing the related water stress. Additionally, in some regions, temporal aspects are crucial due to the high variability of water availability. Consequently, an annual assessment might be misleading regarding crop choices within and among different regions. A temporal resolution is therefore essential for proper life cycle assessment (LCA) or water footprint of crop production. For this purpose we develop a water stress index (WSI) on a monthly basis for more than 11,000 watersheds with global coverage. The median and average watershed area are 1327 and19591 km^2, respectively. The WSI ranges from 0.01 (least water scarcity) to 1 (maximal water scarcity), and quantifies the fraction of water consumed of which other users are potentially deprived of. Moreover, irrigation water consumption for 160 crop groups is calculated on a monthly basis and on a high spatial resolution (<10 km). Crop water footprints (WFP) are calculated by multiplying monthly WSI with monthly crop irrigation water consumption and by summing the result over the cultivation period. With these results we facilitate a new level of detail for WFP analysis.

We estimate global irrigation water consumption in the year 2000 at 1.21*10^{12} m^3/a, with an average WSI of 0.44. The regional pattern changes considerably with higher temporal resolution and therefore in many regions it is relevant to consider monthly WSI. Changes are also shown to be sensitive to crop types due to different growth patterns, which might lead to increasing or decreasing water footprint. Additionally, we examine the role of different conceptual assumptions for the definition of water footprint characterization factors, which can be expressed as marginal and average figures. WSI is a marginal characterization factor. However, a practitioner may favor an alternative average factor to match impact assessment with the given goal and scope of the study. An average characterization factor allows for calculating WFP of a whole region as well as the global annual WFP of agriculture, which is estimated at 3.5*10^{11} m^3-equivalents. This number can be interpreted as water consumed in an extremely water-stressed situation and therefore highly depriving others of its use.

1. Introduction

Irrigation is the dominant human activity leading to water stress, with environmental consequences on the local and global level. Agriculture is responsible for ~85% of total global water consumption and ~70% of water withdrawal (Shiklomanov, 2003). Water consumption is not uniformly distributed, and varies spatially depending on many factors such as cultivated crops, irrigation techniques, soil type, and water availability. Another main determinant for the total annual water consumption in agriculture is the climate, which, commonly, has a temporal variability and influences growing seasons. This high variability is not common in industrial water use such as power production, which is the other major water consuming economic sector (Pfister et al., 2011a; Mekonnen and Hoekstra, 2011a). Therefore, in global analyses the water consumption of crops is mostly calculated on a monthly basis (Pfister

* Corresponding author. Tel.: +41 44 633 75 71.
E-mail addresses: pfister@ifu.baug.ethz.ch, stpfiste@ethz.ch (S. Pfister), bayer@erdw.ethz.ch (P. Bayer).

0959-6526/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2013.11.031

et al., 2011b; Mekonnen and Hoekstra, 2011b). In these analyses, irrigation water consumption is referred to as “blue” water consumption (BW). This is in contrast to “green” water consumption, which refers to natural water supply by soil moisture/precipitation.

Global water consumption can be assessed in different ways [e.g. 1,4,5], and one of the most established ones is the water footprint (WFP). However, the WFP is not well specified, and its definition has even led to confusion in the past. While the original suggestion was calculating WFP by plain aggregation of water consumption volumes (e.g. (Mekonnen and Hoekstra, 2011b)), this is not anymore considered a full WFP (ISO, 2013). The main shortcoming of this approach is that water consumption is entirely equated to environmental damage, without accounting for regional vulnerabilities. On the other hand, for reporting water scarcity issues related to products and services, the WFP was defined in-line with carbon footprint and life cycle assessment (LCA) (Pfister and Hellweg, 2009; Ridoutt and Pfister, 2012, 2010). A recent UNEP resource panel report compared the different available water-related assessment procedures and revealed their similarities as well as the deficiencies of the plain volumetric approach (McGlade et al., 2012). Calculation of water consumption related impacts is optimally done based on specific regional characteristics (including socio-economic analysis). For an efficient analysis of processes in the supply chain, related impacts need to be integrated in a spatially explicit model. These processes are often major contributors to the overall WFP and require coupled water stress and consumption assessment to avoid the loss of spatial detail (Feng et al., 2011).

The framework of LCA is standardized by ISO (ISO, 2006a; ISO, 2006b) and its use has been established in industry over the last decade. LCA consists of four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. It is an iterative process and one purpose of the interpretation step is to advise how to improve the analysis when first or preliminary results are available. Sensitive factors, relevant processes and parameters, system boundaries and modeling procedures are identified and may need to be critically reviewed or further developed. In fact, water footprint analysis follows the same strategy (McGlade et al., 2012), and impacts of consumptive water use are also embedded as an impact category in LCA (Frischknecht et al., 2008; Bayart et al., 2010). In general, impacts in LCA can be addressed on midpoint and endpoint level (Jolliet et al., 2004). Midpoint assessments are based on characterization factors (CF) that quantify environmental consequences within impact categories caused by specific emissions or resource consumption (e.g. CO_2-emission contributing to global warming potential). Some CF account for effects on endpoint level which consider potential damage to areas of protection (mainly Human Health, Ecosystem Quality and Resources). Typically, impacts on midpoint-level are further modeled along the cause-effect chain to arrive at a few endpoints, which for instance indicate loss of human life (typically measured as disability-adjusted life years (DALY) (WHO, 2013)) or loss of ecosystem quality caused by emission of CO_2−equivalents (Goedkoop et al., 2009) for the case of global warming potential.

Various impact assessment methods to assess the water footprint co-exist for the different impact levels (Kounina et al., 2013). The methods available for global scale analysis have a limited spatial or temporal resolution. This is due to the lack of data, and to limit the computational effort and method complexity. However, to capture the highly variable impact of irrigation on a regional scale, a fine spatial resolution is necessary, accounting for hydraulic conditions (e.g. in different watersheds), climate, and crop cultivation. Temporal variability is affected mainly by climate and seasonal growing. Still, most impact assessment methods provide annual CF, and only one is available on a monthly basis, but on the expense of a coarse spatial resolution and lack of global coverage (Mekonnen and Hoekstra, 2011c). One main contribution of the present work is to introduce monthly midpoint CF with global coverage and high spatial resolution (>11,000 watersheds). We enhance the most commonly used CF “water stress index” (WSI, (Pfister et al., 2009)) for monthly assessment. The WSI serves as a characterization factor in LCA and ranges from 0.01 to 1.00 following a logistic function. The WSI can be interpreted as the water deprivation proportion caused by water consumption, that is, how much of the water consumed is considered to be taken away from downstream users (humans and/or ecosystems). While this cause-effect assessment is mainly of conceptual nature, it is useful for identifying hotspots of water consumption impacts in an LCA or WFP study (Kounina et al., 2013), or for analyzing future scenarios (Chiu et al., 2012; Pfister et al., 2011c). However, to address impacts of water consumption in higher detail, local, site-specific analysis might be necessary, especially if crop production is the foreground system in the analysis, such as concluded for the WFP of wine production in New Zealand (Herath et al., 2013). The distinction of foreground and background (e.g. supply chain) processes is a question of the level of detail in an LCA or WFP study and should be defined in its scope definition.

With our study we facilitate a new level of detail for WFP analysis. However, the improved temporal resolution is not the only focus: we also examine the role of different conceptual assumptions for the definition of WFP characterization factors. The objectives of this work thus are (a) improvement of monthly estimates on crop water consumption, (b) evaluation of monthly vs. annual crop water footprints on a high spatial resolution (c) analysis of marginal vs. average approach in water stress characterization (WSI) and (d) analysis of total water footprint caused by agriculture. In the following sections), the calculation methods for irrigation water consumption, annual and monthly CF, as well as average and marginal CF are presented. Global variability of irrigated water consumption is subsequently assessed by averaging of estimates from different calculation procedures. This is followed by a comparison between results for marginal and average CF, and finally the benefit from improved temporal resolution is elaborated. The new assessment methodology is applied to 160 crops irrigated in global agriculture.

2. Material and methods

2.1. Crop irrigation water consumption

Irrigation water consumption of 160 crops and crop groups is modeled on a spatial resolution of 5 arc minutes ($\sim$10 km) and on a monthly basis based on CROPWAT (FAO4.3 ed., 1999). To account for the fact there are different standard methods available to calculate crucial hydrological parameters such as evapotranspiration and effective precipitation, each arising from different conceptual assumptions, we average the results from different methods, to obtain more robust estimates. This approach also accounts for the fact that even high resolution data on crop cultivation or hydrology may be inaccurate, not up-to-date or incomplete. Often irrigation is not well reported, and this may be considered in the calculation by including an estimated proportion of irrigated area. As described in detail in our previous work (Pfister et al., 2011b), we distinguish four different procedures to quantify irrigation water consumption, or blue water: we used the two methods integrated into CROPWAT to calculate effective precipitation and applied each of these to the equations assuming (a) full irrigation ($BW_{CROPWAT}$) and (b) deficit irrigation ($BW_{deficit}$). $BW_{deficit}$ is calculated by multiplying $BW_{CROPWAT}$ with the reported proportion of irrigation (Siebert et al., 2007). The four derived results are combined to determine a range with lower ($BW_{deficit}$) and upper ($BW_{CROPWAT}$) bound, and the arithmetic mean has previously been taken as the best estimate of the expected value (BW_{arith}) (Pfister et al., 2011b). As an alternative, here the geometric