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Reply on RC2

Abdul Wahab Siyal et al.

Author comment on "A conceptual framework for including irrigation supply chains in the water footprint concept: gross and net blue and green water footprints in agriculture in Pakistan" by Abdul Wahab Siyal et al., Hydrol. Earth Syst. Sci. Discuss.,
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Reply to Anonymous Referee #2

We would like to thank the editors for handling the review process and the reviewer for his/her valuable comments. We thank Referee #2 for the comments and suggestions on the manuscript. We have addressed all the comments from the reviewer as shown below and done the necessary modifications in the manuscript.

Reply to the comments

The study shows a conceptual framework of water footprint accounting for irrigated croplands or districts. The improvement from the existing knowledge is a more detailed records of the blue water footprint related to irrigation supply networks. But it is not true as mentioned by the author, there are already several studies account for the irrigation canals related blue WF. My concerns start from the innovative aspect of the study. So that the title seems to be too ambitious to reform the concept of the WF. I think it is more likely an improvements in terms of regional agricultural water footprint accounting in cubic metre per year, specifically in irrigated fields supplied by artificial canals and reservoirs. As for the study content itself, it is really hard to convince me that such conceptual framework can be easily applied to other regions, given such high requirements of input data. So I recommend to resolve following concerns. 1. The graphical abstract is not totally relevant to the study. The study did not accounting for any virtual water flow. The scale of the study is from only water supplier to farmer. Grey water is not discussed in the proposed framework. 2. Figure 1 is not clear and hard for readers. 3. Figure 2 is the core, why not indicate clearly the key components in the framework on the scheme? Which processes constitutes the so called gross or net water footprint, etc. 4. The structure of the text is a mass, there is no section number since 'Results'. The conceptual framework hides in the system analysis for the study case. Please carefully re-arrange the text body to highlight the main information of the study. Only the case? Or the conceptual framework with a case showing? 5. In the discussion, it would be much more helpful to provide a input list and possible collection or monitoring measures. 6. I am confused about the inclusion of the WF of weeds. Can you explain?

Response: Thank you for your valuable comments that helped us to rethink how we need

to formulate our study. We propose in this study a more explicit conceptual framework of the water footprint compared to the last version that was published in 2011 (Hoekstra et al., 2011). At that time, ten years ago, Arjen Hoekstra and his team already formulated the concept. Basically, the whole concept, including the supply chain thinking of blue water supply, is there. However, in the calculation examples in the manual, the irrigation supply chain is not worked out. Also for green water, at that time, no framework was given for green WFs of other plants rather than crops. It was in 2014 that Joep Schyns and Arjen Hoekstra made an assessment of blue water footprints that explicitly included the irrigation supply chain. It is true that there are more studies that also included an irrigation supply chain, however, a conceptual framework is missing. We, therefore, propose to make the irrigation supply chain explicit in the concept, which introduces two new definitions, i.e. of the net and gross blue and green WFs. We are aware of the fact that this might change the study outcomes of earlier studies to a large extent. Probably outcomes of existing studies underestimate especially blue WFs in those cases where large irrigation supply chains exist.

After the introduction of the extension of the concept, we applied this extension for the blue water footprint to Pakistan, because there all blue water flows that can showcase the extension exist. Especially the huge data source from available water management studies helped a lot to work out the gross WF concept.

We fully agree with the reviewer that there are already several studies that account for the blue WF related to irrigation canals. During our review process of available literature, however, we found that a fully developed methodology to address the WF of supply chains in the literature is lacking. WFs of irrigation networks were introduced by Schyns and Hoekstra (2014) who applied the concept to assess the WF of Morocco using canal and field irrigation efficiency with the fraction of evaporative losses from canal networks. This was the first straightforward method to quantify supply network losses, however, without considering the hydrological cycle of the basin. Yuguda et al. (2020) quantified the blue WF of water storage and conveyance for irrigation including seepage losses from a canal system. Their study, however, does not differentiate between seepage to accessible and non-accessible water stocks. Cao et al. (2014), Sun et al. (2016) and Luan et al. (2018) carried out regional level irrigation WF accounting using a water balance approach using the information on irrigation efficiencies to estimate water losses from a source to a crop field. Those studies did not consider return flows and differences between consumptive water use (beneficial and non-beneficial) and non-consumptive use (recoverable and non-recoverable flows). Feng et al. (2021) gave an overview of WF accounting studies for crop production for the period 2002-2018. They included five quantification approaches for the WF of crop production: (i) the field crop water requirement; (ii) the field soil water balance; (iii) the regional water balance; (iv) remote sensing, and (v) the field measured water balance. For the regional water balance, they emphasized the importance of water losses during the delivery processes, especially if one considers the climate and soil characteristics of the study area, indicating that supply chain losses are relatively large and can affect the WF values.

On the basis of the above-mentioned arguments, including water supply chains and its losses is not a matter of just an improvement in terms of regional agricultural water footprint accounting but requires a comprehensive conceptual framework that is in line with water footprint definitions from the manual (Hoekstra et al., 2011).

The studies mentioned above aimed to incorporate supply chain losses based on traditional irrigation efficiency approaches. This water management approach is not completely in line with the WF concept, because part of the lost water might remain available for consumption, e.g. part of the irrigation water might seep into groundwater stocks. If this occurs in the same basin and to an accessible freshwater groundwater stock, water would not be consumed because it can be used again. If the water seeps to

brackish groundwater stocks, it is a real loss and should be accounted for. Consumptive water use in one part of a catchment or basin can impact water users and uses elsewhere in the catchment or basin. To account for this phenomenon, Batchelor et al. (2017) proposed a fractional water accounting analysis which draws attention to the relevance of return flows and differences between water consumptive use (beneficial and non-beneficial) and non-consumptive use (recoverable and non-recoverable flows) in space and time (Gleick et al., 2011; Perry et al., 2009; Batchelor et al., 2017; Simons et al.; 2020). For a regional level WF accounting, we need to adopt a full-scale water balance approach with hydrological characteristics of a specific basin. Any approach, water management (traditional efficiency) or fractional water accounting are solely not enough to fit within the WF definition. Our proposed conceptual framework, including the net and gross WF, would provide a more complete picture of the freshwater system in a specific catchment or basin.

The innovation of the paper is that it extends the actual conceptual framework to explicitly include total human water consumption related to the production of a specific product in the water footprint studies, proposing a way to make explicit the water footprint of supply chains within the already existing methodology (i.e. irrigation supply network and non-beneficial evapotranspiration). When applied for blue water in Pakistan, we show the huge difference between net and gross blue WFs for this specific case.

- The graphical abstract is not totally relevant to the study. The study did not account for any virtual water flow. The scale of the study is from only water supplier to farmer. Grey water is not discussed in the proposed framework.

Response:

The terminology of embedded water and later virtual water was first introduced by Tony Allan (Allan, 1998) and later adopted and worked out into the water footprint concept by Arjen Hoekstra, who introduced the concept for the first time in an expert meeting on virtual water. At that meeting also Allan was present and since then they have always been in close contact. The terminology of virtual water was not only applied by Hoekstra and his team, it is also applied on the website of the Water Footprint network to explain the water footprint concept (see for example <https://waterfootprint.org/en/water-footprint/national-water-footprint/virtual-water-trade/>). A product water footprint is defined as the water consumed for the production of a product including supply chains, so virtual water. This is exactly what our graphical abstract shows, the virtual water chain which forms the basis of a water footprint.

The reviewer is right that the grey WF was not mentioned in our proposed framework. It is an interesting proposal though to also include the grey WF in the irrigation supply chain. Also, there water pollution might occur generating a grey WF. We will include the grey WF in the proposed framework and adapt the graphical abstract.

- Figure 1 is not clear and hard for readers.

Response: We thank reviewer #2 for this valuable comment. We will replace Figure 1 with an adapted version that is more clear. However, with respect to the comment that it is hard for readers to understand actually justifies our arguments that for complex basins like the Indus basin, the WF of growing a crop, as was done in most existing studies, does not give a complete picture of water consumption if we do not include supply chains.

- Figure 2 is the core, why not indicate clearly the key components in the framework on the scheme? Which processes constitute the so called gross or net water footprint, etc.

Response: Thank you for this comment. We will adopt the reviewer's suggestion and

make necessary revisions and corrections in the figure and in the corresponding text to clearly indicate key components of the framework.

- The structure of the text is a mass, there is no section number since 'Results'. The conceptual framework hides in the system analysis for the study case. Please carefully re-arrange the text body to highlight the main information of the study. Only the case? Or the conceptual framework with a case showing?

Response: We thank reviewer #2 for this valuable comment. We followed the suggestions and re-arranged the necessary changes in the text. Section numbers are included.

- In the discussion, it would be much more helpful to provide a input list and possible collection or monitoring measures.

Response: Thank you for your valuable comments. In the discussion section, we will highlight important and possible monitoring measures.

- I am confused about the inclusion of the WF of weeds. Can you explain?

Response: The WF of crops is well mentioned in the literature and the method to estimate the green WF is available from the WF manual (Hoekstra et al., 2011). However, in general, when estimating the green WFs of crops, the WFs of weeds are not taken into account, e.g. weeds in water bodies or on the crop field itself. That is our argument to also include weeds because it is unavoidable that weeds grow next to crops and these weeds also consume water. Although irrigated agriculture is intensive, weeds are not only present in the crop fields, but in Pakistan also in the supply chains, e.g. on the banks of the watercourses and field channels. If these supply chains are poorly managed, like in the case of the agricultural water infrastructure in the Indus basin of Pakistan, weeds might add to the net WF and cause a total gross green WF.

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