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## Reply on RC1

Abdul Wahab Siyal et al.

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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 #1

We would like to thank the editors for handling the review process and the reviewer for his/her constructive comments. We thank Referee #1 for the comments and reply to each of the points below. We insert our responses under each separate comment. We have adopted most of the suggestions for improvement and made the necessary modifications in the manuscript.

## Reply to the general comments

### General comments

The paper presents a framework to account the water footprint (WF) of an irrigation supply network next to the water footprint of growing the crops in the field, and applies this framework to the case of the Pakistani part of the Indus river basin, which hosts a large irrigation supply network. It concludes that the WF of the irrigation supply network is significant compared to the WF of growing the crops, which indicates that WF reduction in agriculture should not merely focus on the farm, but also on the water supply network. I support the need to explicitly assess the WF of irrigation supply networks, which are often excluded from WF assessment studies. However, this paper suffers from a number of flaws which I outline under the specific comments below.

**Response:** We thank the reviewer for his positive comments on the need to address the WF of irrigation supply networks. The suggestions of the reviewer have been very useful to improve the quality of the manuscript.

## Reply to the specific comments

### Specific comments

- The novelty of this paper is overstated. The claimed innovation of the paper is the development of a framework that includes irrigation supply networks in the WF concept. First of all, the Global Standard for Water Footprint Assessment (Hoekstra et

al., 2011) explicitly considers the WF of these supply networks: see Figure 3.6 on page 43 of Hoekstra et al. (2011). Judging from lines 97-99, the authors are aware of this, but this is not reflected from bold statements in the paper, e.g. the first listed highlight and the second sentence of the abstract. The authors should be more modest and nuanced in their statements on the innovations of the paper. Maybe the authors rather meant to say that applications of and elaborations on how to account the WF of irrigation supply networks are sparse in literature. Although the focus of many WF studies on agriculture may have been on the WF of growing the crop in the field only, there are several studies that did account for the WF of the irrigation supply network as well. See the review by Feng et al. (2021)

[<https://doi.org/10.1016/j.ecolind.2020.106962>] – concretely, the RWB approach in Table 1 – which lists at least two studies that are not cited and discussed in this paper: Cao et al. (2014) [<https://doi.org/10.1007/s11269-014-0607-1>]; Sun et al. (2016) [<https://doi.org/10.1016/j.jclepro.2015.06.123>]. Since such previous studies already pointed towards the relevance of the WF of irrigation supply networks, it is not clear what new insights this paper brings.

**Response:** Thank you for your comments. We are aware of the proposed framework in the WF assessment manual, one of the co-authors of this paper was also a co-author of the manual. However, including water consumption of the irrigation supply networks and non-beneficial evapotranspiration were at that time not fully considered in the framework. See for example Figure 3.1 in the manual that only identifies the evapotranspiration of crops as the basis for the green and blue water footprint (WF) in a catchment area. Next Figure 3.2 shows the process WFs as the basic building block for all other WFs. The figure does not specifically mention the supply chain of the water itself, only the production process of a specific product. Figure 3.3 showing the production chain of livestock products starts with the production of feed in agriculture and only includes a direct WF, excluding the WF of the irrigation supply chain or losses due to weeds. Equation (1) in the manual shows how to calculate the blue WF, i.e. assessing WFs in a process step, without disaggregating nor mentioning the water supply chain. Box 3.3, on the “Data sources for the calculation of a blue WF”, introduces the methods and data to estimate blue WFs of CROP GROWING without considering the WF related to the irrigation supply network. Equation 2 introduces the calculation of green WFs, but only for crops and wood. Possible losses because of evapotranspiration of weeds are not disaggregated nor considered. We fully agree that the manual already announces the need to also include the WFs of the blue water supply chain, however, it was not comprehensively considered in 2011. Moreover, the WF studies including the water supply chain are still scarce. For example, the widely used huge database on WFs for crops and livestock products on the website of the Water Footprint Network of Mekonnen and Hoekstra (2011, 2012) gives a huge set of WFs per crop, per province per country, excluding the supply chain of blue water or losses of green water.

How to make the assessment and what data to use is given in box 3.8, again excluding the water supply chain. Finally, on page 134 it is stated that: “The blue water evapotranspiration can be calculated as the total evapotranspiration as simulated in the scenario with irrigation minus the estimated green water evapotranspiration. Note that, over the growing period as a whole, blue water evapotranspiration is generally less than the actual irrigation volume applied. The difference refers to irrigation water that percolates to the groundwater or runs off from the field”.

From the above it is clear that the manual already identified the issue of WFs in supply chains for blue water, but in the calculation equations and examples it was excluded, and green water losses were not mentioned at all. We therefore think it is justified to introduce the gross WF concept to develop and enrich what is already there.

We emphasize that the aim of this paper was to introduce an all water including concept of

the consumptive part of the WF. We therefore not only introduced the concept of the gross blue WF, but also of the gross green WF. Next, we applied this concept to blue water in Pakistan, our case study. We mention in the paper that Hoekstra et al. (2011) already indicated that not only crop evapotranspiration, but also consumption related to water storage, transport, and irrigation should be accounted for. We further reviewed the WFs of irrigation networks introduced by Schyns and Hoekstra (2014), a publication that came after the publication of the manual in 2011, and very well shows how the initial concept has developed further. That study applied the concept to assess the blue WF and irrigation losses of Morocco, like two other similar studies, Yuguda et al. (2020) and Luan et al. (2018) who were also cited in this paper. We adopted the valuable suggestions to also include Feng et al. (2021), Cao et al. (2014) and Sun et al. (2016) who provide information on supply chain water losses.

During our review process of available literature we came across the need to develop a framework addressing the WF of supply chains because literature on this aspect is sparse and not fully developed. For the quantification of the WFs for our case study, we used traditional conveyance and application efficiencies from water management studies and included this in the WF concept making use of two disciplines. We argue that if water remains available, e.g. a flow from surface water to accessible groundwater, this is not a loss as argued in traditional water management studies, but not in the water footprint concept. In this way we also show the relevance of distinguishing between surface and groundwater, quantifying the net and gross blue WFs separately for surface and groundwater.

We also argued that the whole river basin operates as a large canal system where the water is controlled by a complex anthropogenic infrastructure including link canals, barrages, headworks, siphons, and irrigation canals. The natural river flow is completely controlled by human-made structures. This means that all freshwater flows in the human-made network that are not available anymore can be considered as water consumption or blue WF. However, seepage to a fresh groundwater stock is not considered as a loss, while seepage to saltwater stocks, heavily polluted groundwater, non-recoverable drainage outflows, and open surface evaporation from waterlogged areas are considered non-recoverable losses.

To calculate the irrigation WF and to quantify the gross blue WF, we included the evaporation and non-recoverable seepage losses at the basin and field level from each contributing supply chain link. We further calculated each water supply chain efficiency per link of the supply chain. From each supply chain efficiency only non-recoverable losses were calculated, i.e. seepage losses to salt groundwater sinks, losses that become part of fossil groundwater, and drainage outflow, including non-beneficial evaporation. In the case of the Pakistani part of the Indus river basin, we identified two types of losses: evaporation, and seepage to non-accessible water stocks, e.g. salt water reservoirs or deep groundwater.

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 incorporate 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.

- Terminology is confusing and not in line with existing literature in the field.

2a. The paper introduces the terms gross and net WF, for both blue and green water. The net blue WF is equal to the blue WF of the process of growing a crop. The gross blue WF is equal to the blue WF of the process of growing a crop plus the WF of the irrigation supply

network. It is not clear to me, why we would call this net and gross blue WFs. Both refer to gross (or total) water consumption, as opposed to 'net (or additional) water consumption', which is a term that is used in LCA studies and refers to the difference in the ET of a human-made system (e.g. a crop field) and the ET of natural vegetation. So, I would argue that in both cases – with or without considering the irrigation supply network in addition to the process of growing the crop – we have a gross WF, but the scope of the system differs. There is no need to introduce a new term like gross/net WF for this.

**Response:** WF assessments differ from LCA assessments. In this study we aimed to expand the WF terminology in such a way that we stick to existing goals and definitions. We adopted the term net and gross WF from irrigation water management studies and in this way bridged the WF concept and water management studies by including the strong points of both approaches. Net or irrigation blue WFs are similar in both disciplines. However, we adapted the terminology of gross WF to the WF concept showing the strength of both approaches. In water management studies, the gross irrigation requirements account for losses of water incurred that might be avoided during conveyance and application to the field, however, without considering return flows and evaporation losses. This is expressed in terms of efficiencies (conveyance and application efficiencies). We proposed the gross blue and green WFs including actual water consumed by humans (evaporation + non-recoverable return flows).

2b. I do see the relevance of distinguishing between beneficial and non-beneficial water consumption, as others have done (Jägermey et al., 2015; cited in the paper), but it is confusing to then label the beneficial part as 'net WF' viz. the WF of growing a crop (lines 272-273), since the WF of growing a crop itself contains beneficial (transpiration) and non-beneficial (evaporation from the soil and intercepted water) flows.

**Response:** We agree that the WF of growing a crop itself contains beneficial (transpiration) and non-beneficial (evaporation from the soil and intercepted water) flows. This has to do with the water flow from the crop roots to the stomata in the plant leaves transporting nutrients. At the same time, plants need to take in carbon dioxide for the photosynthesis process to grow. This means that water evaporation (i.e. transpiration) cannot be avoided. It is very difficult to calculate the transpiration of water by crops. One needs a model to estimate these water flows. E.g. Gerbens-Leenes and Nonhebel (2004) showed this relationship. However, in actual water management and WF studies normally evapotranspiration of the crops is assessed, indicating not only transpiration but also evaporation from the soil around the crop. For that purpose also models, e.g. Penman Monteith, or satellite data are used. In our view it depends on the definitions one applies on what is beneficial and what is non-beneficial. Our purpose was to stick as much as possible to existing WF definitions as proposed in the manual that calculates evapotranspiration rather than transpiration.

2c. On several occasions (e.g. lines 99-100; 312-314) it is mentioned that the blue WF or growing a crop based on the irrigation requirements method can be considered as "the minimum amount of blue water needed in the production chain of an agricultural blue WF". This is a confusing statement, because this method assumes that crop water requirements are met by irrigation (line 271), i.e. representing a full irrigation strategy. Although other irrigation strategies are possible (deficit, supplemental) that use less blue water since not all crop water requirements are met, intentionally.

**Response:** Irrespective of any irrigation strategy or irrigation method 'the minimum amount of blue water needed in the production chain of an agricultural blue WF' is the minimum water that is evapotranspired by the crop associated with a given irrigation system/strategy. In our case study, which is the agricultural area in Pakistan, the irrigation strategy is to fulfill crop water requirements, always. It can of course be that in other situations this is not the case. This is also what we say in line 100, where the crop

water needs are explained, in contrast to water losses in the supply chain. If water requirements are NOT met, supply chain losses, as a fraction of the irrigation supply, are smaller.

2d. The term 'irrigation WF' is often used in this paper to refer to the blue WF of the irrigation supply network. This is confusing since other scholars in the field have used the term 'blue WF of irrigation' to refer to the consumptive use of irrigation water on the crop field next to the 'blue WF of capillary rise' which refers to the contribution of shallow groundwater to crop ET (Chukalla et al., 2015 [<https://doi.org/10.5194/hess-19-4877-2015>]; Zhuo et al., 2016 [<https://doi.org/10.1016/j.advwatres.2015.11.002>]).

**Response:** We thank reviewer #1 for this valuable comment. We replaced term 'irrigation WF' with 'irrigation supply network WF' in the text to avoid confusion and make it more clear.

- The title, abstract and introduction of the paper mention that green WFs (related to weeds) are assessed, but the methods and data description is incomplete for this aspect and results on green WFs are completely absent; the entire results section focuses on blue water. The authors suggest to add the green ET of weeds on the crop field to the WF of growing a crop. The question is to what degree this is already included in previous studies. Often the green WF of crops has been estimated with the approach of multiplying FAO Reference ET ( $ET_0$ ) with crop factors, and using this to estimate actual ET with a soil water balance model. This approach to estimate actual ET of a crop field may include the ET from weeds present below the crop canopy already to some degree. Furthermore, one may argue that irrigated agriculture is often rather intensive, meaning that measures are taken (use of herbicides) to minimize the presence of weeds on the crop fields, such that the additional ET caused by weeds is hardly relevant.

**Response:** In this paper we first present a holistic approach to quantify blue and green WFs by extending the existing conceptual framework. We then applied the extended concept to a case study, i.e. the assessment of gross blue WFs and K values for agriculture in Pakistan. This conceptual framework could be applied to other case studies. In section 3.1 line 345 of the theoretical framework, we mentioned that 'This framework is also applicable to the green WF'.

We agree with reviewer #1 that the green WF of crops is well mentioned in literature and the method to estimate the green WF is available, e.g. from the FAO through the reference ET ( $ET_0$ ). 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. However, we did not make the assessment of green WFs of weeds, this could be the focus of another study.

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 water courses and field channels. If these supply chains are poorly managed, like is the case of the agricultural water infrastructure in the Indus basin of Pakistan, weeds might add to the total gross green WF. The use of herbicides to minimize the presence of weeds on the crop fields is useful to decrease weed WFs. Both issues require more research and were not addressed in here.

- An irrigation supply network serves multiple farmers who grow different crops. How to attribute the WF of the irrigation supply network to these different users and uses? This is an interesting question that is not addressed in this paper, since it assesses the WF of agriculture in the study area as a whole.

**Response:** Thank you for this comment. In our proposal for the gross WF we comply to WF and also virtual water definitions in such a way that we include the water needed for consumption that is used at another location than where the final product is produced, so in the whole chain.

- Equation 7 needs more explanation to be understood. For example, it is not clear why you multiply the three elements in the equation. It seems to me there might be some double-counting through this multiplication, since  $L_{ii}$  is calculated based on  $L_i$  (Eq 9) and  $L_{ii}$  based on both  $L_i$  and  $L_{ii}$  (Eq 10).

**Response:** Equation 7 gives efficiency at the basin level and that is why we need to multiply all 3 major contributing losses (storage, transport and field application).  $L_i$ ,  $L_{ii}$  and  $L_{iii}$  are representing each link loss as mentioned in the method section in detail. Furthermore, we checked carefully all equations and found them accurate without double counting. This is because  $L_{iii}$  depends on  $L_{ii}$  and  $L_{ii}$  depends on  $L_i$ .

- Equations 11 and 12 define the Gross Blue WF which was already defined in Eq 3. How do these relate?

**Response:** Equations 11 and 12 are in line with equation 3. Equation 3 is the general and conceptual expression of the gross blue WF, while equations 11 and 12 are derivations from equation 3 useful for the calculations and making a distinction between gross blue surface and groundwater.

- Equation 13. I was surprised to see that you calculate NetBlueWF as a fraction of the gross blue WF. Why didn't you calculate the WF of growing a crop using the bottom-up approach ( $ET_o$ , Kc factors, etc)? At least that would be an interesting verification of the result of Eq 13.

**Response:** The net blue WF can be calculated along two different routes, top down and bottom up. In our study we first applied the top down approach, using the difference between gross blue WF and the losses to arrive at the net blue WF. In a next step, this net WF was validated with data from literature that used the  $ET_o$ , Kc factors, etc. If gross blue WFs and efficiencies are known the net blue WF can be calculated. Next, it can be validated with results from a bottom up approach. We validated our approach with WF data from literature. For example blue WFs for the province Punjab from our study are similar to the results from Mekonnen and Hoekstra (2010) who used the bottom up approach. We further compared our results at the basin level with Ullah et al. (2001), Laghari et al. (2012) and Cheema et al. (2016) who used a bottom up approach. We next add in the discussion: 'Our results are also in line with the results of various studies which used satellite data and the latest water accounting modeling approaches to quantify basin scale efficiencies. For example, Van Steenberghe and Gohar (2005) estimated that 79% of pumped groundwater originated from surface water irrigation and non-consumed return flows. Karimi et al. (2013) reported a full basin scale efficiency of 84% and Simons et al. (2020) found 71% efficiency for the Pakistani part of the Indus basin'.

- Equation 14. You say that you adopted this equation from Schyns & Hoekstra (2014), but they defined K totally different as it appears from their paper, based on conveyance and field application efficiency and a fraction of losses in the irrigation canal network that evaporates. How does their definition relate to yours?

**Response:** We exactly used the definition of K introduced by Schyns and Hoekstra (2014) as the ratio of the blue WF of the irrigation supply network (we used Gross blue WF – Net blue WF which is the irrigation supply loss) and the blue WF of crops at the field level (net blue WF). Where Schyns and Hoekstra included conveyance and field application efficiency and a fraction of losses in the irrigation canal network that evaporates, we also included

those losses. However, we excluded water flows from surface water and groundwater back to groundwater stocks, because they remain available and are not considered a loss. That is where we deviated from traditional water management studies that provide efficiency numbers based on flows that are not considered losses according to WF definitions.

- You conclude that the water losses from storage reservoirs are negligible. That is a remarkable outcome considering that Schyns & Hoekstra (2014) conclude that “evaporation from storage reservoirs is the second largest form of blue water consumption in Morocco, after irrigated crop production”. Also Hogeboom et al. (2018) show that the WF of reservoirs (in total and the part attributed to irrigation) are significant compared to the WF of irrigation on the crop field. How do you interpret and explain your outcome?

**Response:** In Pakistan, the surface area of the reservoirs is very small compared to the surface area of the total canal network, which is the largest in the world. We explained this system in our System analysis where Figure 1 shows the reservoirs and the enormous canal network with its huge surface. That is why the evaporation from the reservoirs is relatively small in Pakistan. However, in other countries this might be different.

We included the evaporation of the main reservoirs in Pakistan using evaporation numbers for that country. These numbers deviate from the situation in Morocco. Moreover, the study of Hogeboom et al. (2018) did make a calculation for the reservoirs in Pakistan, however, they only included a reservoir that functions as a source of municipal water supply. We used the evaporation for the three large reservoirs for agriculture, the Mangla, Tarbella and Chasma reservoirs. We included this aspect in the discussion section.

- Looking at Figure 5 I wonder: How do losses in one command area relate to other command areas considering they are interconnected via the supply network (Figure 1), such that crops produced in area A may have a WF in areas B, C, D, etc.?

**Response:** Thank you for this comment. This is very much in line with our answer to your comment 5. Yes, it occurs that a gross blue WF for a specific crop in area A may have a (partly) supply chain WF in another area. This is because the supply chain of the water is long and brings the water from the inlet (here the Indus river) via different links eventually to the crop field where the evapotranspiration takes place. Again, this is in line with WF definitions that distinguish between direct and indirect water consumption.

- The first point of the Discussion again stresses that this study shows that previous studies underestimated the WF of crops (b/c they explicitly focused only on the WF of growing the crop in the field). Such a claim should be substantiated by a quantitative comparison of the outcomes of this study and several previous studies (incl. those mentioned under point 1 of this commentary), which is not present.

**Response:** Thank you for your valuable comments. The main aim of this study was to indicate that including a water supply chain is very relevant. It is not only the evapotranspiration of a crop that determines the WF, as was the focus of many earlier studies. E.g. Mekonnen and Hoekstra, (2010) etc. It was Schyns & Hoekstra (2014) who for the first time showed how relevant it is to include the irrigation losses. By giving this example for Pakistan, a country with very large irrigation supply chains, we emphasized the need to also include these water supply chains. This is because it might support to decrease blue WFs. We included a quantitative comparison of the outcomes of this top down study and several previous studies using a bottom up approach (including those mentioned under point 1 of this commentary in the revised version of the manuscript).

- Lines 587-592: You conclude that the WF of the supply network is very large compared

to the WF on the farm, such that the focus should shift from on-farm WF reduction measures to measures to reduce the WF of the supply network. Also, you point out the latter involves other actors (policy makers) than the farmers. I would argue that this is a good reason to separately assess the WF of the irrigation supply network and the WF of growing the crops on farm, rather than trying to merge them in one indicator (the gross blue WF in this paper). In case you do the latter, you attribute part of the WF of the supply network (which you actually don't do explicitly in this paper, as mentioned under point 4 in this commentary) to the farmer, while this part of the WF is outside the farmer's control. Side note: You can argue whether this is actually out of the farmer's control, since the group of farmers in a command area can take collective action to ask for measures to improve the supply network to combat water losses.

**Response:** Thank you for this comment. In our paper we argued that the assessment of the gross WF is very relevant, next to the net blue WF. We not only included the gross WF though, but also the K value defined as the ratio of the losses and net blue WF. This indicates the size of the losses compared to the often applied (net) blue WF calculated with a model (Kc value etc. or derived from satellite data). The supply chain of the water is indeed partly outside the control of the farmer, as the WF of animal feed not grown by a livestock farmer himself is outside the control of the farmer. However, it is relevant to provide insight into the processes that determine the size of the gross WF and the losses to be able to decrease their size. In Pakistan, the individual farmer cannot control the maintenance and distribution of the water, except the small water courses near to the farms, the other links are the responsibility of governmental organizations, in this case the state of Pakistan. We emphasized that it is relevant to show and quantify the sizes of net and gross blue WFs, and suggested options to decrease the differences between them. However, this is not really a task of researchers but more a policy task. Collective action, as a process of cooperation amongst various stakeholders, including businesses, governments and civil society, is a learning process and can sustain decision making and prioritize actions.

## Reply to the technical comments

### Technical corrections

L78-79: The grey WF refers to the volume of freshwater to assimilate pollutants (not polluted water).

**Response:** Agreed. Changed the sentence accordingly.

L150-152: First sentence mentions that irrigation supply networks are included next to the WF of growing the crop and green water as well. Second sentence states that the focus is on blue crop water use. This is contradictory.

**Response:** Thank you for this comment. We changed these sentences into: 'This study includes two parts. The first part proposes an extended WF concept, including gross and net blue and green WFs. The second part applies this concept to the Pakistani part of the Indus basin and assesses the blue gross and net WF'. We include this text in our Introduction to make the purpose of the study more clear.

Figure 2: Can be improved. Consistently show water flows as arrows and water stocks as boxes. Currently, this is not consistent (e.g. return flows, precipitation and seepage as a box). Precipitation and rainfall appear as separate boxes, why? Same for ET and ET+E. Why ET+E? You probably mean ET from land + E from open water?

**Response:** Thank you for this suggestion. We improved Figure 2.

L340: LostReturnflow is defined here differently than in line 298.

**Response:** Thank you, we adjusted this. We moved the second definition to the first one, because it simply gives more detail.

L484: It is not clear how GrossBlueWFgroundwater has been calculated. The same as for surface water it reads. Yet that seems odd. Does the GrossBlueWFgroundwater depend on total withdrawals from groundwater minus the SFA fraction, which related to groundwater recharge from seepage from surface water infrastructure?

**Response:** For groundwater we used the same approach as for surface water. The only difference is that the supply chain is far shorter, groundwater is pumped up at the place where it is used.

L634-635: I suppose this is not true when surface water is transported over large distances (as opposed to groundwater which is often pumped and used the same site), which also costs energy.

**Response:** In our case study area, there is a canal irrigation system that functions by gravity, energy is only needed for the maintenance of the canal network. The energy to provide surface water in Pakistan is far smaller than the energy to pump groundwater. See for example Siyal et al. (2020). A shift from groundwater pumping to properly maintained gravity-fed canal systems decreases energy use and CO<sub>2</sub> emissions by 31–82% and increases surface water availability by 3%–10%.

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