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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

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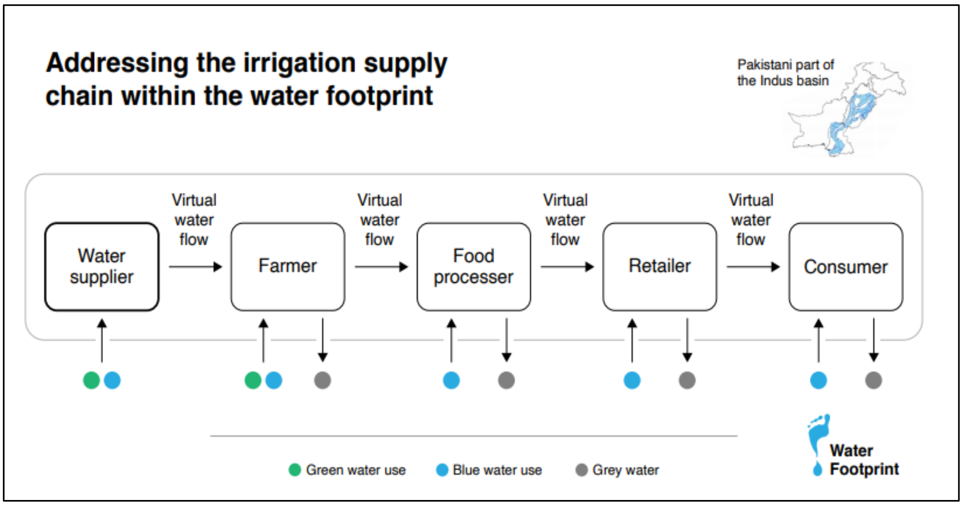
Graphical Abstract



Highlights

- The water footprint conceptual framework should include irrigation supply chains.
- The framework does not consider water that remains available and recoverable.
- To improve agricultural water use efficiency, supply chains need to be considered.
- Hitherto, agricultural water footprint studies have underestimated water consumption.
- Improvement of water footprints requires water management adaptations from policy.

Abstract

The water footprint (WF) concept is a generally accepted tool introduced in 2002. Many studies applied water foot printing, indicating impacts of human consumption on freshwater, especially from agriculture. Although the WF includes supply chains, presently it excludes irrigation supply chains and non-beneficial evapotranspiration, and calculations for agriculture start from crop water requirements. We present a conceptual framework distinguishing between traditional (net) WFs and proposed gross WFs, defined as the sum of net WFs and irrigation supply chain related blue WFs and as the sum of green WFs and green WFs of weeds. Many water management studies focused on blue water supply efficiency, assessing water losses in supply chain links. The WF concept, however, excludes water flows to stocks where water remains available and recoverable, e.g. to usable groundwater, in contrast to many water management approaches. Also, many studies focused on irrigation technology improvement to save water. We argue that not only irrigation technology should be considered, but whole water supply chains, also distinguishing between surface and groundwater, to improve efficient blue water use in agriculture. This framework is applied to the Pakistani part of the Indus basin that includes the largest man-made irrigation network in the world. The gross blue WF is 1.6 times the net blue WF leading to a K value (ratio of gross and net blue WF) of 0.6. Surface water losses vary between 45 and 49%, groundwater losses between 18 and 21%. Presently, efficient irrigation receives much attention. However, it is important to take irrigation supply chains into account to improve irrigation efficiency. Earlier WF studies showing water scarcity in many regions underestimate agricultural water consumption if supply chains are neglected. More water efficient agriculture should take supply chain losses into account probably requiring water management adaptations, which is more a policy than an agriculture task.

Keywords: Water footprint; Conceptual framework; Net water footprint; Gross water footprint; K value; Irrigation supply chain; Pakistan

1. Introduction

Globally, freshwater of good quality is a scarce natural resource in many river basins. Recently, Mekonnen and Hoekstra (2016) showed that the world faces a huge water scarcity problem affecting around four billion people. Also, the Organization for Economic Co-operation and Development (OECD) indicated that in the future agriculture will encounter large water shortages, especially in China, the US, and India (OECD, 2017).

Today, human water management strongly influences water flows and consumption in river basins. In the eighties of the last century, it was expected that, especially in the water-scarce Middle East countries, wars over water would occur (e.g. Gleick, 1993). However, this has never happened. The most important reason was that water-scarce countries import water-intensive agricultural products for their growing populations (Allan, 1993; 2003; 2004). In this way, they compensate for water shortages making use of water resources elsewhere. Allan introduced the term "embedded water" indicating the importance of water coming along with trade flows and later renamed the term "virtual water" defined as the water needed to produce agricultural commodities (Allan, 1993). Hoekstra quantified and further elaborated the concept and introduced the “water footprint” (WF) in 2002, defined as the use of freshwater resources (cubic meters), consumed or polluted, to produce a commodity in the full supply chain (Hoekstra, 2003). The concept includes three water colors: green, blue, and grey. The green WF is defined as rainwater consumption, the blue WF is the consumption of ground and surface water, and the grey WF is the amount of freshwater needed to assimilate polluted water to meet accepted ambient water quality standards. The first WF studies quantified crop WFs. The study of Chapagain and Hoekstra (2004) about the WF of nations calculated WFs per crop per country at a global scale. The database was later updated and extended by Mekonnen and Hoekstra (2010a; 2010b) who distinguished green, blue, and grey WFs for a large number of crops per country on a provincial level. They showed, for example, that in the Pakistani part of the Indus basin, most crops depend on irrigation (blue) water.

The WF assessment manual explains how to use the WF concept (Hoekstra et al., 2011) and forms the basis for WF calculations. The databases available on the Water Footprint Network website provide many WFs, e.g. for crops (Mekonnen and Hoekstra, 2010a) and animal foods (Mekonnen and Hoekstra, 2010b). For agriculture, green and blue WFs were calculated as the crop water requirements (CWRs) over the growing period and were expressed per unit of yield. If a green water supply is not enough to fulfill the CWRs, additional blue (irrigation) water can fulfill the crop water needs. To calculate the WF of an agricultural product, not only the evapotranspiration from the crop is taken into account, but also the next steps in the production chain, e.g. water for production in the food industry, and all the water consumed in the chain to arrive at the final WF (Hoekstra et al., 2011). In the same way, one could argue that to produce a crop not only the water consumed by the crop, i.e. evapotranspiration, but also the water consumption in human-made water supply chains and green water consumption by weeds should be included. 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. This would mean that the WF calculated based on crop evapotranspiration is the minimum amount of water needed for crop growth. In blue water supply chains, losses occur so that actual WFs are generally larger than the ones based on evapotranspiration alone. The minimum water amounts can be considered as net blue WFs, while water consumption including supply chains can be defined as gross blue WFs. This would be in a way similar, but in consumption terms, to the net and gross irrigation water requirements in the agricultural field, where the net irrigation water requirement does not include losses that are occurring during conveyance, distribution, and field application, as opposed to gross irrigation water requirement (FAO, 2021). WFs of irrigation networks were introduced by Schyns and Hoekstra (2014) who applied the concept to assess the WF of Morocco. They found that in Morocco 15% of the blue WF of agriculture is lost in the irrigation supply chain. Another issue is that part of the irrigation water seeps into groundwater stocks. If this occurs in the same basin and to a 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 on 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). Together with the net and gross WF analysis, this would provide a more complete picture of the freshwater system in a specific catchment or basin.

The irrigation water supply chain can be complicated and long. For example, the Pakistani part of the Indus basin includes storage reservoirs, dams, barrages, and canals (Stewart et al., 2018). Water is lost from the reservoirs and canals because it evaporates or seeps into groundwater (Yuguda et al., 2020). Habib (2010) has shown that water losses in Pakistan can be as large as 40 to 50%. Especially the poor maintenance of the canals is a reason for inefficient water supply to the crop fields (Siyal et al., 2021) as the efficiency of the irrigation system is affected by the way of water transportation, the condition of the canal system, and the irrigation technology (Luan et al., 2018). Traditionally, irrigation water losses in the supply chain were addressed under the classical approach of irrigation efficiency, which is the "ratio of water consumed by crops to total water withdrawals" (Israelsen, 1950). The proportion of irrigation water not reaching the crop is classified as a loss or an "inefficiency" (Pérez-Blanco et al., 2020). There are many studies giving information on irrigation efficiencies, e.g. in the Indus basin irrigation system (IBIS) of Pakistan, e.g. Hussain et al. (2011) quantified a 35% irrigation efficiency in the irrigation supply chain (including canal, watercourse, field channel, and field application) at the basin level. Qureshi et al. (2010) measured a 30% overall irrigation efficiency and Shakir et al. (2010) a 40% irrigation efficiency from the canal head to the field level. Rohwer et al. (2007) mentioned an efficiency of around 32% and another study showed a beneficial irrigation efficiency of 24% (Jägermeyr et al., 2015). However, hitherto, this has not been reflected in the WF studies.

Agriculture is the most important human water-consuming sector amounting to about 85% of total consumption (Pfister and Bayer, 2013). The OECD (2017) has shown that many countries will face water risks for agriculture in the future, including Pakistan in the top ten countries at risk. It is therefore relevant to address water losses in the irrigation supply chain to indicate where losses could be prevented. Considering all water supply chain losses might mean that there is a large gap between net blue WFs and gross water supply (m^3 /ha). However, a comprehensive overview of specific losses in the whole water supply chain is not available in practice yet. Such an overview would support the assessment of the difference between net and gross blue WFs (m^3/ton) and indicate locations where crops can be grown under the most favorable water availability conditions and indicate pathways to decrease WFs.

This study aims to provide a conceptual framework to assess gross WFs that includes the irrigation water supply chain and non-beneficial green WFs. The study focuses on blue crop water use using the Pakistani part of the Indus basin as a case study area because the country has one of the most complicated water supply networks in the world that includes all kinds of flows and stocks (fresh surface water, fresh groundwater, salt, and brackish groundwater, and water constructions, such as reservoirs, dams, canals, irrigation systems). Moreover, because Pakistan is a water-scarce country, where information is available. The main research question is: What is the difference between the net and gross blue WFs in the main agricultural areas in Pakistan, where do the largest losses occur and what are the options for change?

The study provides a detailed spatial overview of the differences between net and gross blue WFs per canal command level in Pakistan. Although the conceptual WF framework has been developed for the Pakistani part of the Indus basin, it can be applied anywhere.

2. System analysis

2.1 Blue water supply in the Indus basin in Pakistan

Pakistan has large agricultural areas, especially in Punjab and Sindh. The major crops are wheat, sugar cane, rice, and cotton (FAO, 2020). Rainfall is limited, so crops need an additional irrigation water supply. The main source of freshwater is the Indus river. The intricate canal network of the Indus basin irrigation system (IBIS) brings freshwater to the crop fields. The network originally was a gravity-fed system originating from ancient times. In the 19th century, when Pakistan was part of an English colony, the network was expanded (Alam et al., 2007). Between 1965 and 2019, when agricultural production went up, the network was even further expanded (Sindh Irrigation Department, 2019). Figure 1 shows a schematic map of the irrigation canal network of Pakistan (Stewart et al., 2018).

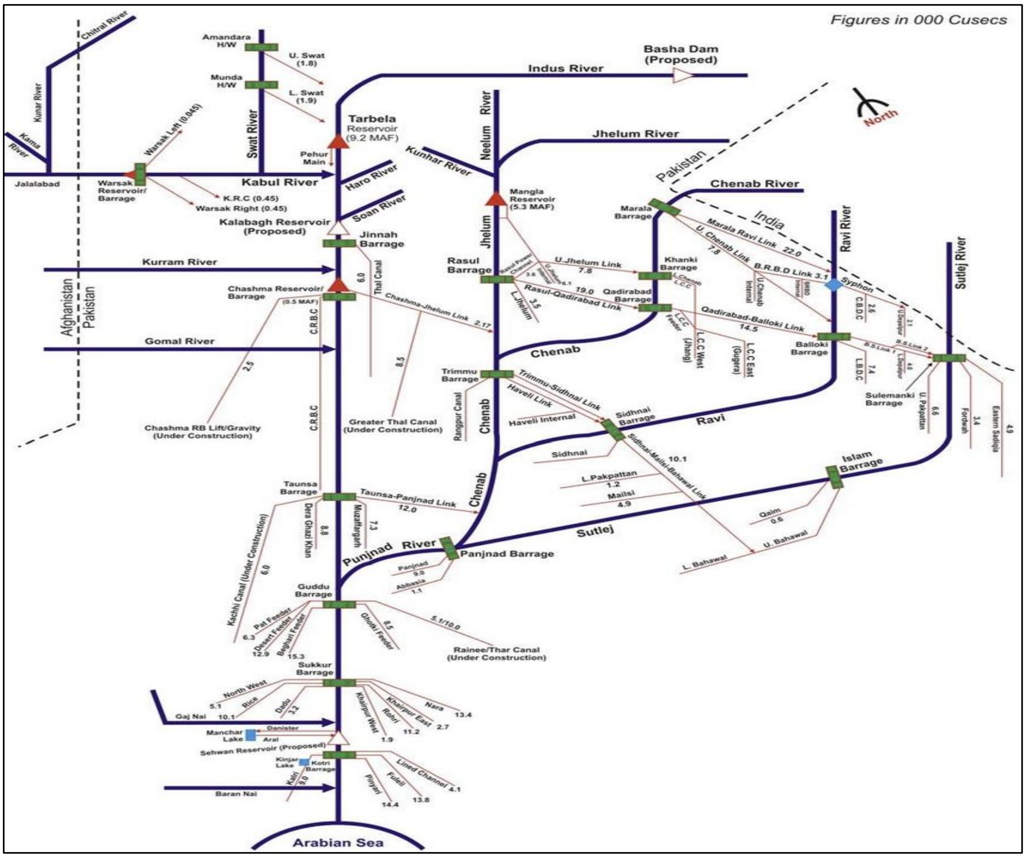


Figure 1. Schematic map of the irrigation canal network of Pakistan (Source: Stewart et al., 2018).

Figure 1 shows the main river, the Indus, the seven smaller rivers, the dams and barrages in the river, and main canals, i.e. the main canals, and linking canals between rivers in the Pakistani part of the Indus basin. The irrigation network systems are developed in the command areas, i.e. the areas irrigated by the water of a specific canal. The Indus basin in Pakistan includes eight major rivers, connected by a network of link canals in the eastern tributaries of the Indus. These link canals mitigate the water deficit from the Ravi, Beas, and Sutlej rivers attributed to India in the Indus Waters Treaty of 1960.

2.2 Surface water infrastructure in the Indus basin in Pakistan

The surface water infrastructure includes the water supply chain, from crop field to source where the inlet of river water occurs, at the field level and the basin level. Figure 2 shows these levels of the water supply chain that includes water inflow from snowmelt and precipitation into the main river Indus and its tributaries, water inlet into the human-made irrigation network, water storage in reservoirs, transport of water to rivers and canals, transport of water to the field channels, irrigation on the field and drainage of water. In every link and flows between links of the supply chain losses occur.

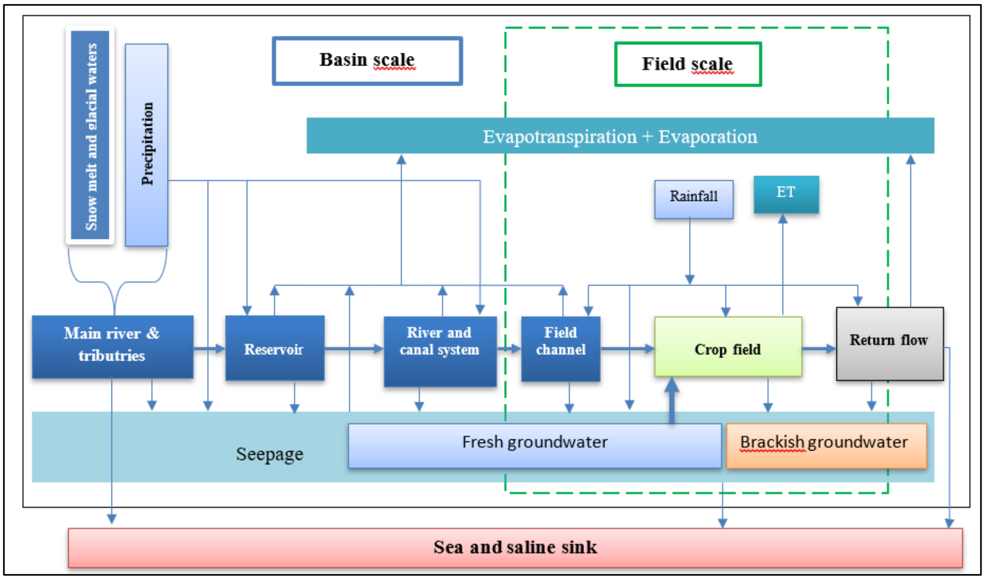


Figure 2. Basin and field-scale level of the irrigation supply chain that includes water inflow from snowmelt and precipitation into the main river Indus and its tributaries, reservoir water storage, water transport to rivers, canals, and field channels, irrigation on the field, and drainage. In every link and between links of the supply chain losses occur.

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 is 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. The following sections describe the irrigation water losses in the supply chain on the basin and field level scale.

2.3 Basin-scale: reservoir losses

Freshwater that enters the human-made irrigation network is often stored first in reservoirs from where it is distributed over the network. Dams creating a reservoir are often not only built for storing irrigation water, but also for other services. In Pakistan, their main function is irrigation water storage, but some smaller reservoirs are also constructed for flood protection and residential and industrial water supply (Hogeboom et al., 2018). Reservoir evaporation is larger than for the original situation before the reservoir was built because reservoirs increase the surface area of the water body. More water is exposed to air and direct sunlight, thus not only increasing evaporation but also seepage. This “lost” water is generally considered consumed water because it is removed from the system (Kohli and Frenken, 2015). For the multipurpose reservoirs, consumed water needs to be allocated over the different services. Seepage water is only considered consumed when it cannot be used again, e.g. if it seeps to brackish or salt aquifers, non-recoverable drains outflows, and evaporates. If it seeps into freshwater aquifers, it recharges groundwater stocks and contributes to water availability.

2.4 Basin-scale: canal losses

Reservoirs that function as a water storage system distribute water over smaller rivers and canals using headworks. From the reservoirs to the fields, the canals become smaller and smaller distributing the water in a precise way, like blood vessels that reach all parts of a body. Water losses occur during this conveying process, including evaporation and seepage. Evaporation from open canals is not recoverable, and can therefore be considered as consumption, while seepage water might contribute to groundwater recharge if it seeps into fresh groundwater stocks.

2.5 Field-scale: water losses from the crop field

After the distribution in the river and canal network, freshwater reaches the crop field. Also, here water is lost. First, water needs to be distributed over the crop field using an irrigation system. Here, water is lost through an inefficient application. For example, through evaporation from surface irrigation or pre-sowing wetting during field preparation (Rauni irrigation). Pre-sowing water application is a practice for the major crops in the basin unless residual soil moisture is available from previous crops. Rauni is usually applied for wheat, cotton, and rice (Briscoe and Qamar, 2005). Another water loss is free surface evaporation due to high water tables, also causing an increase of waterlogged areas, non-recoverable seepage to groundwater stocks, and non-recoverable return flows. Free surface evaporation loss is an important component of irrigation loss causing large waterlogged areas, mostly located in Sindh, the lower Indus basin, and in the Jhelum-Chenab command of Punjab (Habib, 2004).

Finally, freshwater reaches the crops where evapotranspiration takes place. This is unavoidable water consumption and often expressed as a blue water footprint (m^3/ton) (Hoekstra et al., 2011). Irrigation water leaving the crop field and returning to its source or to another waterbody, e.g. to ground or surface water, is termed a return flow or drainage water. Some return flows are applied for irrigation, depending on the water quality. If there are no toxic substances in the return flow, it is suitable for irrigation. This possibility most often occurs when pumping groundwater by vertical drainage. Evaporation and seepage losses are also common for return flows (Luan et al., 2018).

3. Method and data

The study aimed to develop a conceptual framework to assess total agricultural blue and green freshwater consumption, termed gross blue or green water footprint, in a full supply chain, taking all losses in the chain and non-beneficial evapotranspiration into account. The gross blue WF is defined as the sum of the net blue WF (i.e. blue water supply to cover CWRs) and irrigation WFs that include losses. The gross green WF is the sum of net green WFs and non-beneficial green evapotranspiration (e.g. by weeds). The method was applied to calculate gross blue WFs for the IBIS in Pakistan. This section first provides a theoretical framework, i.e. presents the blue and green WF concept and differentiates between net and gross WFs. Second, it identifies losses in human-made irrigation supply chains. In this way, the study calculated total irrigation water requirements. Third, we used the gross blue WF to assess the ratio of total irrigation water supply and total net blue WFs for the crops in the IBIS area, showing that actual water consumption is far larger than assumed.

3.1 Theoretical framework: net and gross blue and green water footprints

Water footprints quantify human water consumption defined as the amount of freshwater used for a certain purpose that, as a result, is no longer available in the same catchment and time period for another purpose (Hoekstra, 2017). The definition differentiates between use and consumption. Especially for the blue WF, this is an important definition because water can be used but is not necessarily consumed. For example, groundwater withdrawn for irrigation might partly return to where it came from, resulting in a difference between amounts withdrawn from groundwater reservoirs and actual amounts of blue water consumed, i.e. blue WFs. To estimate the pressure on blue water resources it is more important to have information on blue water consumption rather than on water withdrawals (Hoekstra, 2013). In this way, according to the Water Footprint Assessment Manual (Hoekstra et al., 2011), the blue WF in a process step, $WF_{proc,blue}$, is calculated as:

$$WF_{proc,blue} = BlueWaterEvaporation + BlueWaterIncorporation + LostReturnflow \qquad (1)$$

Herein $BlueWaterEvaporation$ is the blue water lost by evaporation, $BlueWaterIncorporation$ is the water incorporated in the product and the *LostReturnflow* refers to the part of the return flow that is not available for reuse within the same catchment within the same period of withdrawal, either because it is returned to another catchment (or discharged into the sea) or because it is returned in another period of time.

Another important perspective introduced by the WF concept has been supply chain thinking in water management. For the assessment of water consumption of a product, the whole production chain is included and water consumption in every chain link is taken into account (Hoekstra et al., 2011). Many WF studies have been performed on WFs of agricultural products using this chain approach. For example, there is a large database on WFs of crops and livestock products available on the WF Network website (Mekonnen and Hoekstra, 2010a; 2010b). The system boundary of those studies included agriculture and all processes in the supply chain thereafter, so from farm to fork. For the calculation of the green WFs, assessments are made based on climate data, for grey WFs on nitrogen pollution data, and expressed per unit of crop. For blue WFs, assessments were based on irrigation requirements, i.e. volumes of surface or groundwater consumed for irrigation in agriculture. This amount can be considered as the minimum amount of blue water needed in the production chain of an agricultural product, or as a *net blue WF*:

$$Net\ blue\ WF = BlueWaterBeneficialConsumption + BlueWaterIncorporation \qquad (2)$$

Herein *BlueWaterBeneficialConsumption* refers to the water that is purposefully converted to water vapor, such as through crop transpiration (Perry et al., 2009).

Supply chain thinking might also apply at a larger scale expanding the system boundary to include the supply of blue water for irrigation, or a so-termed *irrigation WF* (Hoekstra et al., 2011; Schyns and Hoekstra, 2014). In many basins, there is a human-made irrigation network that conveys freshwater from a natural system (e.g. from a river or aquifer) to a man-made system, e.g. a crop field. This is for example the case in China where large conveyance pipes bring water from the South to the dry regions in the North (Ma et al., 2005), in Morocco where water is stored in reservoirs (Schyns and Hoekstra, 2014), and in Pakistan where a large canal network conveys water from the Indus to the crop fields (Stewart et al., 2018). Adding the blue WF of irrigation to the blue WF of a crop would give information on the water consumption of a specific crop in its whole supply chain. Adding this volume of water to the net blue WF generates information on what we define as the *gross blue WF* and might provide a tool to optimize water management. We calculate the *gross blue WF* as:

$$Gross\ blue\ WF = BlueWaterBeneficialConsumption + BlueWaterIncorporation + BlueWaterNonBeneficialEvaporation + LostReturnflow \quad (3)$$

Herein *BlueWaterBeneficialConsumption* refers to the water that is purposefully converted to water vapor, such as through crop transpiration. *BlueWaterNonBeneficialEvaporation* is the water that is not purposefully converted to water vapor, such as through transpiration by weeds, evaporation from wet soil, and evaporation losses from reservoirs, canals, or high groundwater table areas. The *LostReturnflow*, or non-recoverable return flow, refers to water that flows without benefit to a sink such as a sea, saline sink, or heavily polluted aquifer, and therefore is not usable. The recoverable return flows are not included as the water reaches a usable aquifer or stream with downstream demand and they are not considered consumption (Perry et al., 2009).

This framework is also applicable to the green WF. According to Hoekstra et al. (2011), the green WF, $WF_{proc,green}$, is the volume of rainwater consumed during the production process:

$$WF_{proc,green} = GreenWaterEvaporation + GreenWaterIncorporation \quad (4)$$

Herein $GreenWaterEvaporation$ refers to rainwater evaporated by crops and $GreenWaterIncorporation$ to rainwater incorporated in crops. One could differentiate between the *net green WF* and *gross green WF:*

$$Net\ green\ WF = GreenWaterBeneficialConsumption + GreenWaterIncorporation \quad (5)$$

And

$$\begin{aligned} Gross\ green\ WF \\ &= GreenWaterBeneficialConsumption + GreenWaterIncorporation \\ &+ GreenWaterNonBeneficialEvaporation \end{aligned} \quad (6)$$

Where *GreenWaterBeneficialConsumption* refers to the water that is purposefully converted to water vapor, such as through crop transpiration from rainwater. *GreenWaterNonBeneficialEvaporation* is the water that is not purposefully converted to water vapor, such as through transpiration by weeds or evaporation from wet soil from rainwater (Perry et al., 2009).

3.2 Losses human-made surface and groundwater supply chain

To calculate the irrigation WF and to quantify the gross blue WF for the IBIS in Pakistan, we included the following surface water losses at the basin and field level: evaporation and seepage losses from (i) reservoirs; (ii) canals (link canals, main and secondary canals, watercourses and field channels); (iii) field application including Rauni (pre-sowing irrigation for land preparation). We calculated the surface water supply chain efficiency, E_{ff}, at the basin level including the efficiencies per link of the supply chain as:

$$E_{ff} = \frac{W_i - L_i}{W_i} * \frac{W_i - (L_i + L_{ii})}{W_i - L_i} * \frac{W_i - (L_i + L_{ii} + L_{iii})}{W_i - (L_i + L_{ii})} \quad (7)$$

where W_i is the surface water withdrawal in the first link of the supply chain and *L (i-iii)* is the water losses in the specific link of the supply chain. We emphasize that the seepage to fresh groundwater stocks is not considered a loss, because, according to the WF definition, the water remains available. Losses are non-recoverable seepage losses to salt groundwater sinks, losses that become part of fossil groundwater, and drainage outflow including non-

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beneficial evapotranspiration. The groundwater efficiency was calculated in the same way as the surface water efficiency.

The first link of the human-made irrigation supply chain is the reservoir. To quantify irrigation water withdrawal to the reservoirs, we subtracted average annual river losses and sea outflow from the river inflows at the river inflow measuring stations. Data on average surface water inflows for the period 1922-2016 of 164 to 182 km^3 /year were taken from Young et al. (2019). Average annual river losses of 10% were adopted from Habib (2004), Ahmed et al. (2007), and Hussain et al. (2011). The average sea outflow from 1975-2016 of 29 to 32 km^3/year was adopted from Young et al. (2019). Water withdrawal to the reservoirs was assumed to be 119.2 to 132.3 km^3/year.

(i) Reservoir storage efficiency

The three reservoirs, Tarbela, Mangla, and Chashma, are mainly applied for irrigation water storage. To calculate reservoir storage efficiency, we assumed that water from reservoir seepage flows to fresh groundwater stocks where it is still available for human use and therefore not considered as a loss. We only assumed evaporation as a loss and allocated these losses to irrigation. The evaporation loss from reservoirs, L_i (km^3/year), was calculated per reservoir as:

$$L_i = \sum_{a=1}^{3} Et_{o(a)} * A_{(a)} * 10^6 \tag{8}$$

Herein $Et_{o(a)}$ is the reference evapotranspiration (mm/year) for reservoir a, $A_{(a)}$ is the surface area of the reservoir a (km^2) and factor 10^6 is applied to convert mm/year to km^3/year. Data on the potential evapotranspiration of the Tarbela reservoir of 2,362 mm/year and of the Mangla reservoir of 1,727 mm/year were taken from Ahmad et al. (1963) and for the Chashma reservoir potential evapotranspiration of 1,466 mm/year was taken from Ullah et al. (2001). Data on reservoir capacity and surface areas were taken from Karimi et al. (2013). See also Table A2 in the Supporting Information. Next, we calculated the efficiency for equation 7.

(ii) Conveyance efficiency

The second link of the irrigation supply chain includes the canals, i.e. the link canals, main and secondary canals, watercourses, and field channels. Water seepage to fresh groundwater stocks was not considered as a loss, but evaporation and non-recoverable seepage were included as a loss. To calculate the efficiency of the canals, we estimated the total canal evaporation and seepage loss, L_{ii} (km^3/year), which includes the losses of the components of the second link, i.e. link, main and secondary canals, watercourses, and field channels, as:

$$L_{ii} = \textstyle\sum_{p=1}^{4}(W_{i(p)} - L_{i(p)}) * E_p * \ E_s \tag{9}$$

Herein $W_{i(p)}$ is withdrawn water per component p of the second link (m^3/year), $L_{i(p)}$ is the water loss per component p of the second link (m^3/year) and E_p and E_s are the fractions of estimated evaporation and seepage losses per component. Data on evaporation and seepage of the link canals of 3% were taken from Lieftinck (1968) and Habib (2004). Of the 3%, 33% evaporates and 67% seeps. Of the seepage losses, 25% goes to fresh groundwater and 75% is a non-recoverable loss (Habib, 2004).

For the main and secondary canals, Lieftinck et al. 1968), Habib (2004), Ahmad and Rashida (2001) and Hussain et al. (2011) reported 25% conveyance losses. Evaporation losses of the main and secondary canals of 5% of the withdrawals were taken from Frederiksen (1992) and Jazira (2006). Of the seepage, 68% seeps to fresh groundwater stocks while the other 32% is non-recoverable (Habib, 2004).

Ahmad and Rashida (2001) and Hussain et al. (2011) reported conveyance losses in watercourses from head to farmgate of 30%. Sahasrabudhe (2011) and Liu et al. (2016) reported evaporation losses from watercourses of 1% of the withdrawals. For the seepage, we assumed that 68% goes to fresh groundwater and 32% is non-recoverable (Habib, 2004).

For the field channels, Lieftinck et al. (1968), Ahmad and Rashida (2001) and Hussain et al. (2011) reported 10% conveyance losses. For evaporation losses, we took an average of 0.63% based on ranges of 0.25 to 1% from Sahasrabudhe (2011) and assumed again that of the seepage 68% flows to for fresh groundwater stock and 32% is non-recoverable seepage. Table A3 in the SI gives an overview of all losses. Next, we calculated the efficiency for equation 7.

(iii) Field application efficiency

The third link of the irrigation supply chain includes field application and Rauni. We calculated the evaporation and seepage losses, L_{iii} (km^3/year), as:

$$L_{iii} = (W_i - (L_i + L_{ii})) * E_{field} * S_{field} \tag{10}$$

Herein $(W_i - (L_i + L_{ii}))$ is the annual irrigation water withdrawal (m^3/year) from the field channels to the crop fields through surface irrigation, including Rauni. E_{field} and S_{field} are the evaporative and seepage fraction losses (%). Data on the field application losses of 25% (evaporation and seepage) were taken from Habib (2004), Ahmad and Rashida (2001), and Hussain et al. (2011). We assumed that of these losses 8% evaporates, while 92% seeps to groundwater. We assumed again that 68% of the seepage flows to a fresh groundwater stock and 32% is non-recoverable. Next, we calculated the efficiency for equation 7.

(iv) Groundwater efficiency

To calculate seepage and evaporation water losses from groundwater withdrawal, we distinguished groundwater losses from field channels and field application. Losses were calculated in the same way as the surface water efficiency. Groundwater recharge and non-recoverable seepage losses from groundwater return flow of 70% and 30% respectively were adopted from Habib (2004).

3.3 Gross and net blue crop water requirement in the Indus basin in Pakistan

Next, we assessed the gross blue water footprint for the total Indus basin, $GrossblueWF_{Total}$ (km^3/year), that when expressed per unit of yield (m^3/kg), is the average gross blue WF, as the sum of the gross surface WF, $GrossblueWF_{surface}$, and the gross groundwater WF, $GrossblueWF_{groundwater}$ as:

$$Grossblue\ WF_{Total} = GrossblueWF_{surface} + GrossblueWF_{groundwater} \tag{11}$$

The gross surface WF, $Grossblue\ WF_{surface}$ (km^3/year), was calculated as:

$$Grossblue\ WF_{surface} = W_i - SFA \tag{12}$$

Herein W_i is the total blue surface water withdrawal in the first link of the supply chain and *SFA* is the groundwater recharge from the surface water infrastructure to a freshwater aquifer. We calculated *SFA* using the fraction of seepage losses per surface water supply link from equation 9 and 10. The $GrossblueWF_{groundwater}$ (m^3/year) was calculated in the same way.

Next, to express the ratio of the total gross blue WF and the net blue WF, *NetblueWF* (m^3/year), we first calculated the net blue WF as:

$$NetblueWF = E_{ff} * GrossblueWF_{surface} + E_{effGroundwater} * GrossblueWF_{groundwater} \quad (13)$$

The ratio of the total gross blue WF and the net blue WF using a factor K was adopted from Schyns and Hoekstra (2014) and calculated as:

$$K = \frac{GrossblueWF_{Total} - NetblueWF}{NetblueWF} \quad (14)$$

Subsequently, calculations were also done per province and canal command area. To assess provincial surface water canal withdrawal, we used the apportioned water withdrawal as agreed in clause 2 of the IRSA accord (Anwar and Bhatti, 2018) and for the canal command areas we took data on canal level diversion assessment from Cheema et al. (2016). For provincial groundwater withdrawal, we assumed that all recharge to groundwater stock from the human-made supply chain is available for pumping. Pumped groundwater per province as a percentage of total pumped groundwater (%) was adopted from Lytton et al. (2021) and at the canal level, groundwater supply data was taken from Cheema et al. (2016). See also the SI Table A4-A7.

Results

Table 1 shows the average blue WF of irrigation, water losses according to traditional water management approaches and the efficiency of surface and groundwater supply per chain link in the Indus basin in Pakistan from 1992 to 2016 using the WF and traditional water management approach.

Table 1. Average blue WF of irrigation, water losses according to traditional water management approaches and the efficiency of surface and groundwater supply per chain link in the Indus basin in Pakistan from 1992-2016

Surface water irrigation	**Blue WF (km^3/year)**	**Efficiency (%)**
Reservoirs (evaporation)	**1.02**	**99.2**
Canals	**26.23**	**85.4**
Link canal evaporation	*1.23*	*99.0*
Link canal seepage	*1.88*	*98.5*
Canal (main & secondary) evaporation	*6.05*	*95.1*
Canal (main & secondary) seepage	*7.74*	*93.6*
Watercourse evaporation	*0.91*	*99.2*
Watercourse seepage	*8.42*	*92.2*
Crop fields	**9.98**	**90.1**
Field channel evaporation	*0.40*	*99.6*

Field channel seepage	*1.90*	*98.1*
Field application evaporation	*4.57*	*95.3*
Field application seepage	*3.11*	*96.8*
Total	**37.23**	**71.0**
	Traditional losses (km^3/year)	**Traditional efficiency (%)**
Total non-recoverable supply chain losses	**37.23**	**71.0**
Recharge to fresh groundwater (recoverable)	**45.61**	48.4
Total	**82.84**	**34.4**
Groundwater irrigation	**Blue WF (km^3/year)**	**Efficiency (%)**
Crop fields	**6.95**	**84.8**
Field channel evaporation	*0.29*	*99.4*
Field channel seepage	*1.28*	*97.2*
Field application evaporation	*3.28*	*92.5*
Field application seepage	*2.09*	*94.9*
	Traditional losses (km^3/year)	**Traditional efficiency (%)**
Total not-recoverable supply chain losses	**6.95**	**84.8**
Recharge to fresh groundwater (recoverable)	**7.88**	**79.6**
Total	**14.82**	**67.5**

Table 1 shows that using the consumption-based WF or withdrawal-based traditional water management approach generates different results. The WF approach generates far smaller losses and higher efficiency than the traditional water management approach. Surface water use efficiency is 71% for the WF and 34% for traditional water management. The difference is due to the large recoverable recharge of surface water to groundwater. Also, for groundwater, the difference is large. WF generates an efficiency of 85%, the traditional approach only 68%, also due to groundwater recharge that is not considered a loss in the WF approach.

Using the WF conceptual framework, the largest surface water losses occur in the canals, especially in the main and secondary canals through evaporation and seepage causing an efficiency of 85%. Efficiency at the field scale is larger than at the canal scale, losses caused by storage in the reservoirs are negligible. The table also shows that surface water irrigation has a smaller efficiency than groundwater irrigation caused by the relatively long supply chain in Pakistan.

Figure 3 shows the average gross and net blue surface and groundwater footprints (km^3/year) per province (Punjab, Sindh, Balochistan, and Khyber Pakhtunkhwa (KPK)), for the country as a whole and the percentage of losses for the period 1992 – 2016.

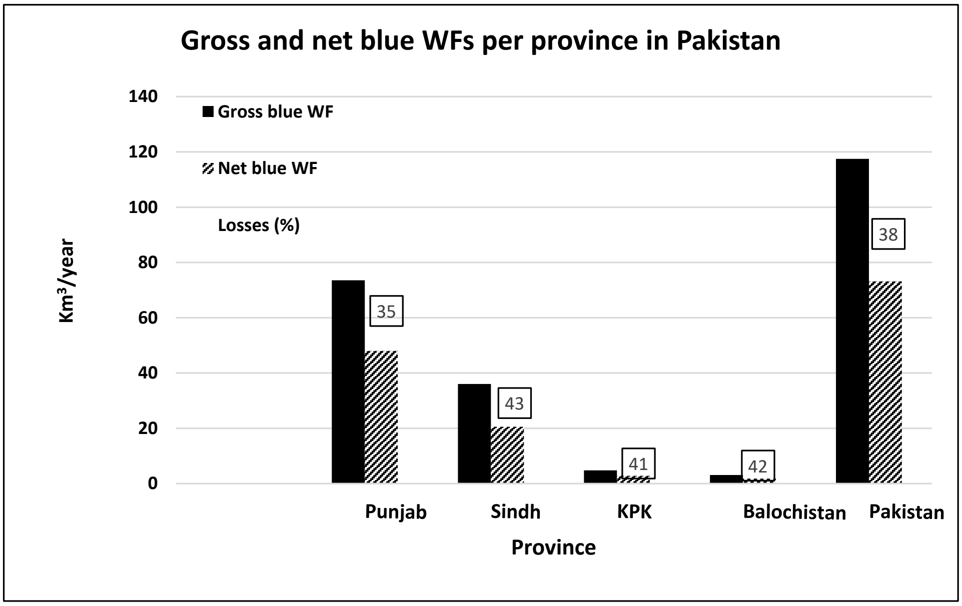

Figure 3. Average gross and net blue water footprints (including both surface and groundwater) (km^3/year) per province (Punjab, Sindh, Balochistan, and Khyber Pakhtunkhwa (KPK), for Pakistan and the percentage of losses for the period 1992 – 2016.

Punjab has the largest gross and net blue WF, but irrigation losses of 35% are relatively small. Sindh has the second-largest blue WFs with losses of 43%. The difference is caused by the type of blue water applied. In Punjab, the fraction of surface water with long supply chains and relatively large irrigation WFs is smaller than in Sindh and groundwater of good quality is available. In Sindh, the groundwater is salt or brackish so that it relies on surface water. Blue water consumption in KPK and Balochistan is relatively small. At the country level, 38% of blue surface and groundwater is lost in agriculture.

Figure 4a-d shows gross and net blue surface and groundwater WFs (km^3/year) per province. Figure 4a gives the gross blue $WF_{surface}$ (km^3/year), Figure 4b the gross blue $WF_{groundwater}$ (km^3/year), Figure 4c the net blue $WF_{surface + groundwater}$ (km^3/year) and figure 4d the K value.

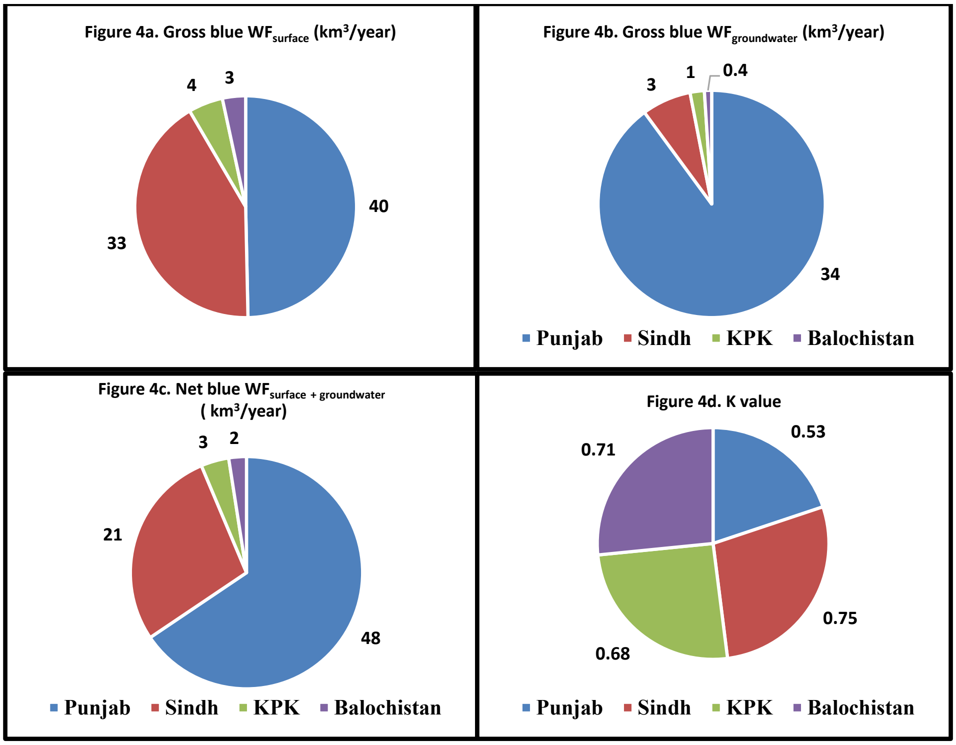

Figure 4a-d. Gross and net blue surface and groundwater WFs (km^3/year) per province. Figure 4a gives the gross blue $WF_{surface}$ (km^3/year), Figure 4b the gross blue $WF_{groundwater}$ (km^3/year), Figure 4c the net blue $WF_{surface + groundwater}$ (km^3/year) and figure 4d the K value. (KPK is Khyber Pakhtunkhowa).

Figure 4a shows that the national gross blue WF from surface water is dominated by Punjab and Sindh, the two main agricultural production sites. Figure 4b shows that the national gross blue WF from groundwater is largest in Punjab, while in the other provinces the contribution of groundwater is small. Figure 4c shows the dominant blue WF of Punjab, followed by Sindh, and the small contributions of KPK and Balochistan. Figure 4c-d shows that the losses compared to the net blue $WF_{surface + groundwater}$ in Punjab are better than in the other provinces, as the K value is 0.53 meaning that almost 47% water is lost. In the other provinces, the situation is worse than in Punjab, with K values between 0.68 and 0.75. These results show that the WF of irrigation forms a relevant contribution to blue WFs.

Figure 5 shows a map of the K values per canal command area of the Indus basin in Pakistan.

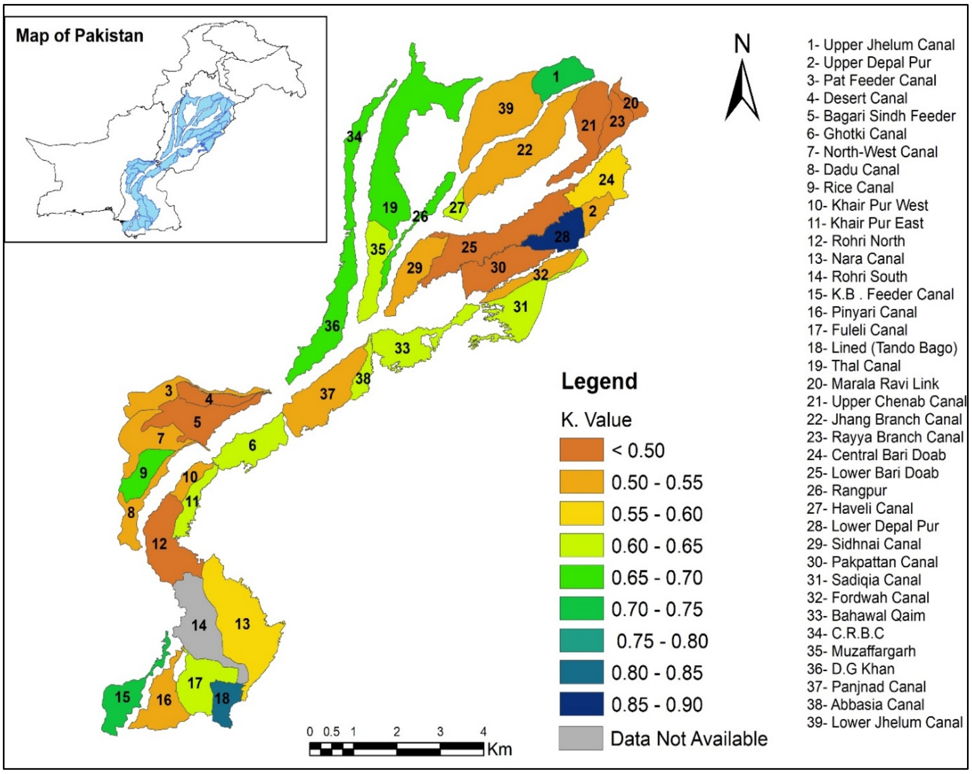

Figure 5. Map of K value per canal command area of Indus basin, Pakistan.

The average K value of the IBIS canal command areas was 0.59, with K values ranging between 0.5 and 0.9. The smallest water losses occur in the East of Sindh and North of Punjab, whereas large losses occur in the South and one canal command in Punjab.

Discussion

- This study introduced an extension of the WF concept in agriculture by including the human-made irrigation supply chain as well as additional green WFs caused by the evapotranspiration of weeds. In this way, using blue WFs in the Indus basin in Pakistan as an example, it identified a large gap between net blue WFs, as calculated in existing WF studies (e.g. Mekonnen and Hoekstra, 2010a), and gross blue WFs calculated here. This means that water scarcity assessments based on net blue WFs might underestimate water scarcity because water consumption is larger than assumed when the whole water supply chain is taken into account. Our study showed that for a WF analysis, it is relevant to focus on complete production chains, including the human-made water supply chain.
- Our conceptual framework differs from traditional water management studies so that blue water seeping to fresh groundwater stocks is not considered a loss, because it remains available for use, in line with the concept of the WF. Our conceptual framework applied to the Indus basin generates larger efficiencies than traditional water management approaches.

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Based on withdrawal-based traditional water management studies, the water use efficiency for both surface and groundwater in Pakistan is around 43% where this study showed an efficiency of 74% if water flows to fresh groundwater stocks were not considered a loss.

- The analysis of losses in the supply chain gives information about hotspots where most losses occur. In our case study, we showed that especially the canals generate the largest water losses so that priority needs to be given to decrease those losses rather than to install more efficient irrigation technology. Several studies also emphasize this perspective (e.g. Simons et al., 2020; Pérez-Blanco et al., 2020). This might be a policy task, while farmers can better address more efficient irrigation technology.
- Our estimates of reservoir evaporation losses are in line with results from Karimi et al. (2013) who quantified losses in reservoirs in India and Pakistan at 1.91 km^3. Evaporation losses of the Pakistani reservoirs quantified by Hogeboom et al. (2018) for the Simly and Rawal of 0.004 km^3 underestimate evaporation. The reservoirs are not designated for irrigation purposes and are very small and used to supply drinking water to Islamabad and Rawalpindi.
- Our results give an indication of gross blue WFs for the Pakistani part of the Indus basin. However, data on losses in separate links of the water supply chain are limited. Therefore, we used general assumptions at the macro level and integrated data from several separate studies to give the overall picture. If more precise information becomes available better estimates can be made. This is also relevant for other countries and basins.
- We distinguished between surface water and groundwater, not only because the irrigation WFs are more favorable for groundwater than for surface water with long supply chains, but also because there is a trade-off between efficient water use and energy use. Groundwater supply requires energy for pumping, and this is far larger than energy for the construction and maintenance of surface water supply (Siyal et al., 2021)
- Recent scientific literature indicates existing flaws in the traditional efficient water use approach in agriculture, making it difficult to solve the water scarcity issues (e.g. Jensen, 2007; Peter et al., 2011; Perry, 2011; Lankford, 2012; Perry et al., 2017; Simons et al., 2020). The extended conceptual WF framework contributes to better insight and shows the most vulnerable links in water supply chains indicating options to decrease blue WFs. Also, for other basins with other characteristics than the Indus basin in Pakistan that suffer from water stress.

Conclusions

This study presents a new conceptual framework to assess gross blue and green WFs. When applied to the Pakistani part of the Indus basin, the gross blue WFs are much larger than the net blue WFs. Losses in the water supply chain can be large and depend on specific efficiencies in separate chain links. For Pakistan, most losses occur in the canals when water is conveyed to the fields. Using the WF conceptual framework, the largest surface water losses occur in the canals, mainly in the main and secondary canals through evaporation and seepage. Efficiency at the field scale is larger than at the canal scale, losses caused by storage in the reservoirs are negligible. In general, surface water application was less efficient than groundwater use. Surface water losses vary between 45 and 49%, while groundwater losses between 18 and 21% dependent on local conditions. There are large efficiency differences among provinces, caused by different factors, such as the ratio of surface and groundwater use or losses to saltwater stocks.

Withdrawal-based traditional water management studies indicated a water use efficiency for Pakistan of around 43% where this study WF showed an efficiency of 74% if water flows to fresh groundwater stocks were not considered a loss.

The distinction between surface water and groundwater in blue WF calculations is relevant, because the irrigation WFs depend on local circumstances and differ between the two water types. Moreover, a trade off between water and energy might occur, because groundwater pumping requires more energy than surface water supply.

Presently, much attention is paid to more efficient irrigation, however, a focus on the supply chain might save more water. For Pakistan, the gross blue WF is 1.6 times the net blue WF leading to a K value (ratio of gross and net blue WF) of 0.6. Also, case studies are needed to assess gross green WFs. Earlier studies showing the net WFs indicating water scarcity in many regions probably underestimated water scarcity if supply chains are excluded. The approach applied for Pakistan is also relevant for other countries and basins when efforts are made to use water more efficiently. More water-efficient agriculture should also take these supply chain losses into account which probably requires water management adaptations, which is more a policy than an agriculture task.

Appendix A: supplementary data

Table A1 shows the average annual river water inflow and outflow of the Indus basin in Pakistan adopted from Young et al. (2019) that were used for the calculation of water withdrawals into the human-made canal system.

Table A1. Average annual river water inflow and outflow of the Indus basin, Pakistan

Inflow and outflow at measuring stations	km^3/year
Inflow Indus (including Kabul), Jhelum, Chenab	170 (± 5%)
Inflow Ravi, Beas, Sutlej	3 (± 10-20%)
Sea outflow	30 (± 5%)

Source: Young et al., 2019

According to Young et al. (2019) there is no complete, consistent, published, total, national water balance of the Indus basin in Pakistan. Therefore, we used river water inflow and outflow estimates to quantify withdrawals into the human-made canal network. These withdrawals formed the basis for the calculations of seepage and evaporation losses in the irrigation water supply chain.

For the calculation of the losses in the first link of the supply chain, we included the evaporation losses from the reservoirs. Table A2 gives the capacity, area, evaporation and evaporation losses from the major reservoirs of the Indus basin in Pakistan, the Tarbela, Mangla and Chasma reservoir.

Table A2. Capacity, area, evaporation and evaporation losses from the major reservoirs of the Indus basin, Pakistan

Reservoir	Capacity[1] (km^3)	Area[1] (km^2)	Evaporation (Et_o) (mm/year)	Evaporation losses (km^3/year)
Tarbela	13.9	260	2362[2]	0.61
Mangla	7.3	250	1727[2]	0.43
Chashma	0.9	6	1466[3]	0.01
Total	**22.1**	**516**	**4820**	**1.05**

[1] Karimi et al., 2013
[2] Ahmad et al., 1963
[3] Ullah et al., 2001

There is a lack of information in the literature about evaporation and seepage losses in each link of a water supply chain (for Pakistan, the canal network). In the Indus basin of Pakistan, it is also difficult to estimate, due to complexity in the size, length, and extent of the canal network which stretches within an area of 16 10^6.ha and falls in different agro-climatic zones. Therefore, we used general assumptions at the macro level for each type of supply chain link based on available information in the literature. Table A3 gives an overview of river and conveyance losses (evaporation and seepage) per supply chain link for irrigation in the Indus basin, Pakistan that were collected form literature.

Table A3. Overall river and conveyance losses (evaporation and seepage) per supply chain link for irrigation in the Indus basin, Pakistan

River and supply chain link	Conveyance losses (%)	Evaporation losses (%)
River	7[a], 13[b] (of the total inflows)	33[g]
Link canal	3[b] (of the diversion)	33[g]
Main and secondary canals	25[c] (of the canal withdrawals)	2-8[h], 8[i]
Watercourse	30[d] (watercourse head to farm gate)	0.25-1[j], 1[k]
Field channel	10[e] (farm gate to crop field)	0.25-1[j]
Field application	25[f] (of surface irrigation)	8[j]

[a] Hussain et al., 2011; Ahmed et al., 2007.
[b] Habib, Z., 2004; Lieftinck et al., 1968
[c] Hussain et al., 2011; Habib, Z., 2004; Lieftinck et al., 1968
[d] Hussain et al., 2011; Ahmad and Rashida, 2001.
[e] Hussain et al., 2011; Lieftinck et al., 1968; Ahmad and Rashida, 2001.
[f] Hussain et al., 2011; Habib, Z., 2004; Lieftinck et al., 1968; Van Waijjen, 1996.
[g] Habib, Z., 2004
[h] Frederiksen, 1992.
[i] Jazira, 2006.
[j] Sahasrabudhe, 2011.
[k] Liu et al; 2016

The seepage losses were calculated by subtracting evaporation losses from the overall conveyance losses.

Table A4 gives the annual groundwater recharge from different sources. It not only includes the recharge from the human-made canal system, but also from rivers in Pakistan.

Table A4. Annual groundwater recharge from different sources

Source	Minimum	Maximum	Average
Rivers	25[a]	40[b]	33
Inter-river link canal network[a,b]	25[a, b]	25[a, b]	25[a, b]
Main canal irrigation network and fields	66[c]	70[a]	68[c]
Groundwater pumping[a]	70	70	70

[a] Habib, 2004
[b] RAP, 1979
[c] FoDP;2012

Table A5 shows the groundwater withdrawal per province (% of total withdrawal) and withdrawal for Pakistan as a whole (km^3/year).

Table A5. National groundwater withdrawal (km^3/year) and withdrawal per province (%) in Pakistan

	Groundwater withdrawal (km^3/year)		
	Min	**Max**	**Average**
Pakistan	43.21	48.01	45.61
	Groundwater withdrawal[a] (%)		
Punjab	90		
Sindh	7		
Khyber Pakhtunkhowa (KPK)	2		
Balochistan	1		

[a] Lytton et al.(2021)

Table A6 shows the canal withdrawals of surface water as agreed in the clause 2 of the IRSA accord adopted from Anwar and Bhatti (2018).

Table A6. Surface water canal withdrawal per province as agreed in clause 2 of the IRSA accord (Source: Anwar and Bhatti , 2018)

Province	**Canal withdrawal[a] (%)**
Punjab	48.9
Sindh	42.6
Khyber Pakhtunkhwa (KPK)	5.1
Balochistan	3.4

[a] Anwar and Bhatti, 2018.

Table A7 gives the irrigated area, evapotranspiration (ETc) (mm) for the Kharif and Rabi season, and canal and groundwater supply (mm) per province in Pakistan. Data were adopted from Cheema et al. (2016).

Table A7. IIrrigated area (km^2), canal and groundwater supply (mm), evopotranspiration (ETc) (mm) for the Kharif and Rabi season per province in Pakistan (Source: Cheema et al. (2016))

Canal command	Area (km^2)	ETc (mm)			Surface water supply (mm)	Groundwater supply (mm)
		Kharif	Rabi	Total		
Thal	10900	420	236	656	516	55
Upper Jhelum	2650	701	419	1120	1031	73
Lower Jhelum	7100	501	395	896	452	171
CRBC	1000	318	269	587	521	108
Marala Ravi	900	577	389	966	385	276
UCL	4200	597	391	988	496	239
LCC	1500	598	425	1023	556	247
Raya branch	1600	512	352	864	346	207
Central Bari Doab	3200	488	380	868	533	140
Lower Bari Doab	7600	644	492	1136	724	297
Rangpur	1700	328	259	587	670	94
UDC	1700	264	427	691	447	186
Haveli	700	565	412	977	597	172
LDC	500	637	475	1112	637	0
Muzfargrah	3250	500	428	928	1260	179
Sidhani	3400	626	462	1088	707	285
Pakpattan	4200	622	478	1100	620	285
Dera Ghazi Khan	3900	466	264	730	1097	126
Fordwah	2200	481	343	824	546	242
Sadiqa	4600	290	230	520	861	170
Bhalwal	3300	422	250	672	818	167
Abbasia	700	426	207	633	475	211
Panjnad	6300	651	338	989	794	306
Pat feeder	3300	796	386	1182	571	241
Desert	1650	743	376	1119	1155	552
Begari canal	4200	795	424	1219	832	373
Ghotki canal	3900	473	232	705	1069	211
Northwest	4600	793	433	1226	763	269
Rice canal	2250	789	427	1216	2102	215
Khairpur West	2400	607	376	983	790	274
Dadu canal	2400	474	315	789	794	276
Khairpur (East)	2900	321	194	515	618	123
Rohri (North)	4700	600	396	996	531	279
Lined canal	2000	454	314	768	546	0
Nara	10000	385	267	652	910	196
Fuleli canal	4200	576	357	933	1220	156
Pinyari canal	4000	526	345	871	869	285

Table A8 shows gross and net blue WFs (km^3/year) and the K value per canal command area in the Indus basin, Pakistan

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Table A8. Gross and net WFs (km^3/year) and K value per canal command in the Indus basin, Pakistan

Canal commands	Gross WFs (km^3/year)	Net WFs (km^3/year)	K value
Thal	4.01	2.40	0.67
Upper Jhelum (UJC)	1.89	1.10	0.72
Lower Jhelum (LJU)	2.96	1.96	0.51
CRBC	0.43	0.26	0.69
Marala Ravi	0.43	0.29	0.48
UCL	2.09	1.42	0.48
LCC	0.83	0.55	0.52
Raya branch	0.62	0.42	0.48
Central Bari Doab (CBDC)	1.43	0.91	0.58
Lower Bari Doab (LBDC)	5.18	3.47	0.49
Rangpur	0.86	0.51	0.68
UDC	0.74	0.48	0.54
Haveli	0.38	0.23	0.65
LDC	0.21	0.11	0.89
Muzfargrah	3.04	1.84	0.65
Sidhani	2.27	1.51	0.50
Pakpattan	2.56	1.73	0.48
Dera Ghazi Khan	3.08	1.85	0.67
Fordwah	1.18	0.79	0.50
Sadiqa	3.10	1.93	0.61
Bhalwal	2.14	1.33	0.61
Abbasia	0.35	0.22	0.59
Panjnad	4.62	3.07	0.50
Pat feeder	1.81	1.20	0.50
Desert	1.91	1.29	0.48
Begari canal	3.40	2.30	0.48
Ghotki canal	3.26	2.03	0.61
Northwest	3.16	2.08	0.52
Rice canal	3.36	2.00	0.68
Khairpur West	1.71	1.12	0.53
Dadu canal	1.72	1.12	0.53
Khairpur East	1.42	0.88	0.62
Rohri (North)	2.58	1.77	0.46
Lined canal	0.70	0.39	0.81
Nara	7.22	4.55	0.59
Fuleli canal	3.74	2.26	0.66
Pinyari canal	3.07	2.00	0.53
Kalri canal	0.40	0.23	0.75

Author contributions

Conceptualization, A.W. Siyal, P.W. Gerbens-Leenes, M.M. Aldaya; Data collection and analysis, A.W. Siyal; Writing original draft preparation, A.W. Siyal.; Editing, P.W.Gerbens-Leenes, M.M. Aldaya; Contribution to study design, P.W. Gerbens-Leenes, M.M. Aldaya.; Visualization, A.W. Siyal, R. Naz.

Competing interests

The authors declare that they have no conflict of interest.

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