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Energy and carbon footprints for irrigation water in the lower Indus basin in Pakistan, comparing water supply by gravity fed canal networks and groundwater pumping

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A B S T R A C T

Irrigation water can come from surface water or groundwater, or a combination of the two. In general, efforts to provide one type or the other differ depending on local circumstances. This study aims to compare energy and carbon footprints of irrigation water provided by either a gravity-fed irrigation network requiring maintenance or a groundwater pumping system. The case study area is the lower Indus basin in Pakistan. For the assessment, the study could make use of data from local governmental organizations. Energy footprints of surface water are 3–4 KJ/m^3, carbon footprints 0.22–0.30 g/m^3. Groundwater has energy footprints of 2100 for diesel to 4000 KJ/m^3 for electric pumps and carbon footprints of 156 for diesel and 385 g/m^3 for electric pumps. Although groundwater contributes only 6% to total irrigation water supply in the lower Indus basin, it dominates energy use and CO_2 emissions. The total energy footprint of surface water in Pakistan is 0.5 10^3 TJ/y, and for groundwater 200 10^3 TJ/y or 4.3% of national energy use. The total carbon footprint of surface water is 36 10^6 kg/y, and for groundwater 16 000 10^6 kg/y or 9% of Pakistan's total CO_2 emissions. Although the contributions of water supply to total energy use and CO_2 emissions are small, they could increase if more groundwater is used. A shift from groundwater pumping to properly maintaining gravity-fed canal systems decreases energy use and CO_2 emissions by 31–82% and increases surface water availability by 3%–10%.

1. Introduction

1.1. Background information

The concept of the water-energy-food nexus was introduced at the Bonn Water, Energy and Food security nexus conference in 2011, organized with some large international organizations including the Food and Agriculture Organization of the United Nations (FAO), the International Food Policy Research Institute (IFPRI), the Stockholm International Water Institute (SIWI), the Energy and Resources Institute (TERI), the World Business Council for Sustainable Development (WBCSD) and the World Wide Fund For Nature (WWF) (Hoff, 2011). The Energy-Water-Food nexus is an approach to address the complicated interrelationships between two important resources, i.e. energy and water, and one of the basic human made products, food. These topics are high on the international policy agenda and are addressed by organizations of the United Nations, like the IPCC, UN-Water and the FAO. Energy, water and food production systems are closely interlinked, but often studied separately. Food production requires water for crops, water supply needs energy, e.g. for canal maintenance or for pumping, while energy needs water, e.g. for cooling a power plant. Especially energy, and related carbon dioxide emissions and climate change, are priorities on the international policy agenda (IPCC, 2014). Proper water management and water supply of adequate quantity and quality is a problem in many countries, e.g. in Asia where more than half of the countries face water insecurity caused by small availability of water or unsustainable groundwater use (UN-Water, 2019). Although many efforts have been made, food insecurity is still a huge problem facing globally two billion food insecure people half of which live in Asia (FAO, 2019).

Globally, agriculture is by far the largest freshwater user, especially irrigated agriculture accounts for 70% of the world's fresh water withdrawal; 90% of this irrigation takes place in arid to semi-arid regions (Viala, 2008). Freshwater resources are usually scarce in these areas and irrigation to supplement precipitation is

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obtained from either surface or groundwater resources often requiring energy to pump or divert water (Zhao et al., 2020). Surface water is often supplied by means of a gravity-fed canal network, e.g. in the lower Indus basin in Pakistan, groundwater is supplied by pumps needing energy to operate (Rao and Malik, 1982). For the operating energy inputs, usually only the energy of pumping water is recorded, while irrigation water by a gravity flow through a canal is considered free of energy costs. Surface water supply by a properly functioning canal network, however, needs operational energy for maintenance, e.g. to remove sediment and vegetation and to strengthen canal banks. Therefore, irrigated agriculture consumes both freshwater and energy. Globally, pumping groundwater for agriculture consumes 23–48% of agricultural energy (Singh et al., 2002). This has become a major concern for irrigation water supply (Fernández García et al., 2014), indicating an increasing dependency on groundwater pumping. The resulting decline in groundwater tables exacerbates this trend. However, energy for collection, extraction and conveyance of freshwater for irrigation is generally considered negligible for gravity-fed systems (Klein, 2005). So there is a need to explore the supply of surface and groundwater irrigation from an energy perspective to address the emerging nexus in terms of freshwater scarcity, efficient water use in agriculture for food production and energy consumption (and related carbon dioxide emissions) to supply irrigation water in two interlinked irrigation systems, irrigation using surface water or groundwater.

1.2. Water-energy-food studies

Many studies have used the nexus approach to indicate relationships between water and food, e.g. water footprint studies quantifying how much water is needed to produce a unit of food (e.g. Mekonnen and Hoekstra, 2011) or studies on water use efficiencies in agriculture (e.g. Kögler and Söffke, 2017). A large cluster of studies exists on the assessment of water volumes needed to provide energy, starting in the last century when Gleick (1994) published the first study on water for energy and energy for water desalination. After that, many followed, e.g. Macknick et al. (2012) and Meldrum et al. (2013), who gave an overview of how much water is needed to provide energy. Likewise, Napoli and Garcia-Tellez (2016) have introduced a framework for understanding energy for municipal water supply and Gerbens-Leenes (2016) has indicated how much energy is needed to supply a unit of municipal water in the Netherlands. Plappally and Lienhard (2012) have shown energy for water relationships for several cases, Cohen et al. (2004) studied energy for water supply in California and Qureshi (2014) has assessed the energy and carbon footprint of groundwater in Pakistan. In Asian agriculture, all aspects of the water-energy-food nexus come together. If proper coordination among different aspects of the nexus is lacking, e.g. between freshwater, agriculture and energy, decisions taken in one sector might influence others causing tradeoffs (Unver et al., 2017).

Especially energy and carbon footprints for groundwater supply can be large. For example, Shah (2009) has shown that in India groundwater pumping accounts for 4% of the total national carbon dioxide (CO_2) emissions. Qureshi (2014) has shown that the contribution of groundwater pumping using electricity and diesel to the total carbon footprint of Pakistan amounts to 1.2% indicating the need to improve efficiency in irrigation to decrease the carbon footprint. Another study in the province of Punjab in Pakistan has shown that energy used for groundwater pumping increased substantially between 1995 and 2010 from 48 to 61% of on farm direct energy use (Siddiqi and Wescoat, 2013). Those authors pointed out the need to improve surface water supply to decrease energy intensive groundwater use. However, lack of canal maintenance leads to inequity and unreliability of surface water supply from upstream to downstream, causing problems of waterlogging due to seepage, leakage and water overtopping of canal banks so that discharge can be reduced by 40–50% (Habib, 2010). Kuper and Kijne (1992) and Habib and Kuper (1996) have addressed gravity-fed irrigation systems in terms of canal network performance, reliability and water saving potentials in Pakistan, but excluded energy for maintenance. Bhutta and Van der Velde (1992) have indicated the importance of equitable surface water distribution in Pakistan, but also excluded energy for maintenance. Silting of canals due to poor maintenance may lead to water scarcity, pushing farmers to pump groundwater (Belaud and Baume, 2002), thereby increasing energy use and CO_2 emissions. So, the main driver of energy demand for irrigation water supply is related to surface water scarcity in the canal network systems (Mekonnen et al., 2015).

In their review paper, Plappally and Lienhard (2012) gave an overview of the energy needed per unit of freshwater for food production, e.g. energy for lifting water (pumping groundwater or surface water) and conveyance. Jackson et al. (2010) analyzed energy consumption at the irrigated field level and Moreno et al. (2010) studied energy for pressurized irrigation systems. Díaz et al. (2011) showed that efficient water use may lead to higher energy demand. Li (2014) indicated the importance of an integrated water and energy policy in China, while Safa et al. (2011) quantified energy per unit area for the construction of water supply sources, conveyance works, and system maintenance and operation.

1.3. Research gap

When surface water supply is limited, e.g. due to insufficient maintenance of canals, farmers start to pump groundwater requiring energy and giving rise to CO_2 emissions. The lack of proper and regular maintenance in canal networks develops tradeoffs towards higher groundwater use and energy demand. To the best of our knowledge no studies have yet assessed the freshwater and energy saving potential associated with the maintenance of gravity-fed irrigation canal systems or compared two water supply systems, i.e. a gravity-fed canal network requiring maintenance and a groundwater pumping system both delivering irrigation water till the farm gate. Available research regarding benefits of better maintenance of canal networks mainly addressed the water perspective. The research gap we identified is that the energy used for pumping groundwater is thus far only linked to the inefficient energy usage at the primary stage of maintaining a canal network system since it is a main driver of high energy demand for groundwater pumping in irrigated agriculture of the lower Indus basin of Pakistan. Yet inefficient energy use is also linked to inefficient water use.

1.4. Contribution to existing knowledge

We reviewed the mechanism of maintenance in the canal network system from an energy perspective and came up with an approach based on available historical data to improve water use efficiency in irrigation and decrease energy use and CO_2 emissions. This study addresses the energy requirements to provide irrigation water to the farm gate and aims to compare water supply, energy and carbon footprints of irrigation water provided by two systems. Our case study area is the Sindh province in the lower Indus basin in Pakistan since it includes one of the largest irrigated agricultural areas in the world with a complex gravity-fed irrigation network, where also groundwater is used when there is a shortage of surface water from the network (Steenbergen et al., 2015). Moreover, official water withdrawal and earthwork data are available, e.g. from the Indus river system authority (IRSA), and Sindh Irrigation Department (2019). Our main research question is: How large is the energy and carbon footprint to supply irrigation water to the farm gate in the province of Sindh in the lower Indus basin in Pakistan by a gravity-fed canal system requiring maintenance compared to a groundwater supply system that needs pumping? Taking the Sindh province as a case study area, we estimate operational energy input and CO_2 emissions for the regular routine maintenance activities in the canal network and compare this with the energy used and CO_2 emissions for groundwater pumping. The study also indicates how much groundwater can be saved by proper canal network maintenance.

1.5. Main objective

The main objective of this study is to address the energy perspective of irrigation water supply, which is important in the context of the water-energy-food nexus in irrigated agriculture throughout the arid and semi-arid regions of the world. This study is the first estimate of energy and water interdependencies comparing a gravity-fed irrigation and a groundwater supply system in agriculture showing both groundwater and energy saving potentials. In water supply systems policy choices affect the energy footprints but also give rise to trade-offs (Gerbens-Leenes, 2016). Our results might support policy to either stimulate proper maintenance of canal networks or groundwater pumping from an energy and CO_2 emission perspective.

First, we give information on the systems for irrigation water supply in the lower Indus basin of Pakistan which consist mainly of gravity-fed canals followed by groundwater pumping. Second, we estimate the operational energy and CO_2 emissions for the maintenance of a gravity-fed canal system and for groundwater pumping for irrigation purposes. The results give energy and carbon footprints per unit of surface and groundwater as well as groundwater savings. Finally results are discussed and put in context.

2. Irrigation water in the lower Indus basin of Pakistan

The lower Indus basin is located in the South of Pakistan (Fig. 1). In the basin, the main irrigation water source is river water from a gravity-fed canal network system diverted from the Indus, followed by a groundwater supply system. River water is diverted at three barrages and fresh groundwater is available along the Indus River (Azad et al., 2003). Over 80% of the irrigated land, however, has salty or brackish groundwater that is not suitable for irrigation (Azad et al., 2003). The estimated groundwater potential is about 25 10^9 m^3 with an annual use of 4 10^9 m^3 (Steenbergen et al., 2015).

2.1. Gravity-fed irrigation canals lower Indus basin

The canal water network system in the lower Indus basin in Pakistan is a gravity-fed system originating from ancient times, later expanded by the English in the 19th century (Alam et al., 2007). Between 1965 and 2019 the system was even further expanded (Sindh Irrigation Department, 2019). The system receives its water from the river Indus, characterized by large sediment loads and large water discharge (Liu et al., 2001). The river flows from high altitudes to the sea, taking the sediments along. Most canals are earthen canals with flood embankments (Mazhar Ali, 1966) losing about 50% of the water (Memon et al., 2013). Normally, irrigation canals are designed in such a way that water flows are constant and no sedimentation or erosion occurs (Mendez V, 1998). In practice though water flows fluctuate. Sediment transport depends on flow conditions. The resistance to water flows is important for flow conditions and is influenced by factors like vegetation or bed roughness (Mendez V, 1998). If sedimentation occurs in a riverbed and the river cannot flow freely anymore, the water always finds another way to the sea creating a new river bed (Havinga et al., 1998). For man-made irrigation canals containing water between banks this is not the case and too much sedimentation will eventually hinder the gravity-fed irrigation system (Mazhar Ali, 1966). This necessitates earthwork to remove the sedimentation. Previously this was often done by manual labor but more and more machines were used mainly because sediments are heavy and waterlogged (Mazhar Ali, 1966). Sediments are used for bank strengthening or brought to the agricultural fields (Mazhar Ali, 1966).

Energy is needed for the construction of the canal system and its annual maintenance to remove the sediment to keep the water flowing, to strengthen the banks and to transport the sediments. Maintenance requires energy to fuel machines which normally run on diesel (FAO, 1992).

2.2. Groundwater supply systems

If the canal water system does not provide enough water, for example if too much sediment upstream blocks a proper water flow, farmers downstream lack sufficient water. If that occurs and groundwater of good quality is available, farmers are starting to pump. Without losses, the energy used for pumping water based on lifting 1000 m^3 water from 1 m depth at 100% efficiency is 9.8 MJ (Karami et al., 2012). However, in practice energy losses occur. Depending on groundwater tables, farmers use either diesel or electric pumps (Qureshi, 2014). For groundwater extraction, the dynamic head and pumping system efficiency are crucial parameters that influence energy requirements of pumping. For relatively high groundwater tables with a dynamic head of around 15 m, normally diesel pumps are used. If groundwater tables are lower with a dynamic head around 60 m, farmers apply electric pumps (Qureshi, 2014). Diesel pumps are more energy efficient than electric pumps if the whole production chain of energy, the so called energy required for energy (ERE), is taken into account because in electricity generation losses are taking place.

3. Method and data

For the assessment of operational energy and CO_2 emissions for the maintenance of a canal irrigation network to supply surface water and pumping groundwater, the study compared two different systems: (i) a gravity-fed irrigation system and (ii) a groundwater pumping system both supplying freshwater till the farm gate. The Sindh province in the lower Indus basin of Pakistan in 2019 was the case study area. Since the construction of the gravity-fed system occurred over a period of centuries (Mazhar Ali, 1966) energy for water infrastructure and production of pumps was excluded from our study. System (i) needs energy for maintenance, i.e. energy for machines, clearing and transporting sediment and strengthening banks; system (ii) needs energy for groundwater pumping.

The assessment includes two clusters of steps. The first cluster assesses the operational energy needed for proper maintenance of the canal irrigation network. The second cluster calculates the energy for pumping groundwater. Next, energy requirements are combined with CO_2 emission data. Fig. 2a and b shows the calculation steps for the assessment of operational energy for maintenance of a canal irrigation network to supply surface water and for pumping groundwater in the lower Indus basin (Sindh), Pakistan in 2019 till the farm gate.

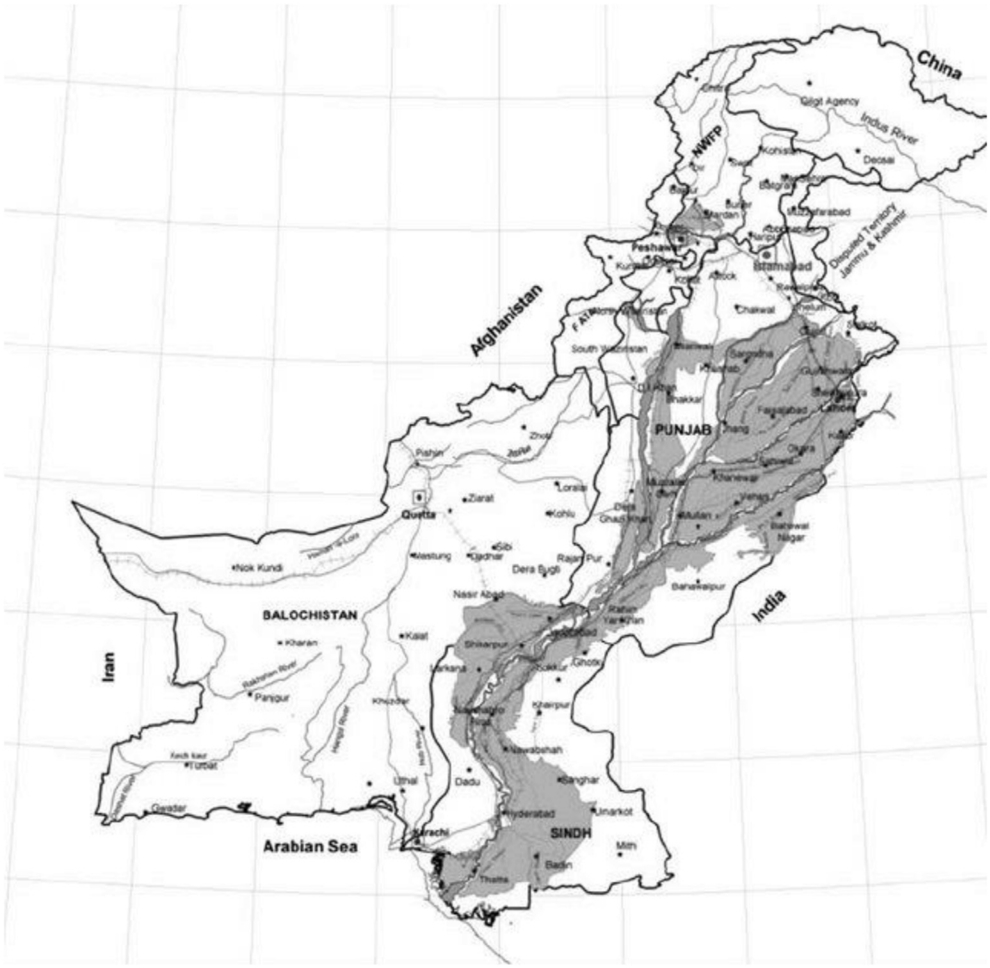

Fig. 1. Indus basin irrigation system of Pakistan (Source: Basharat et al., 2014).

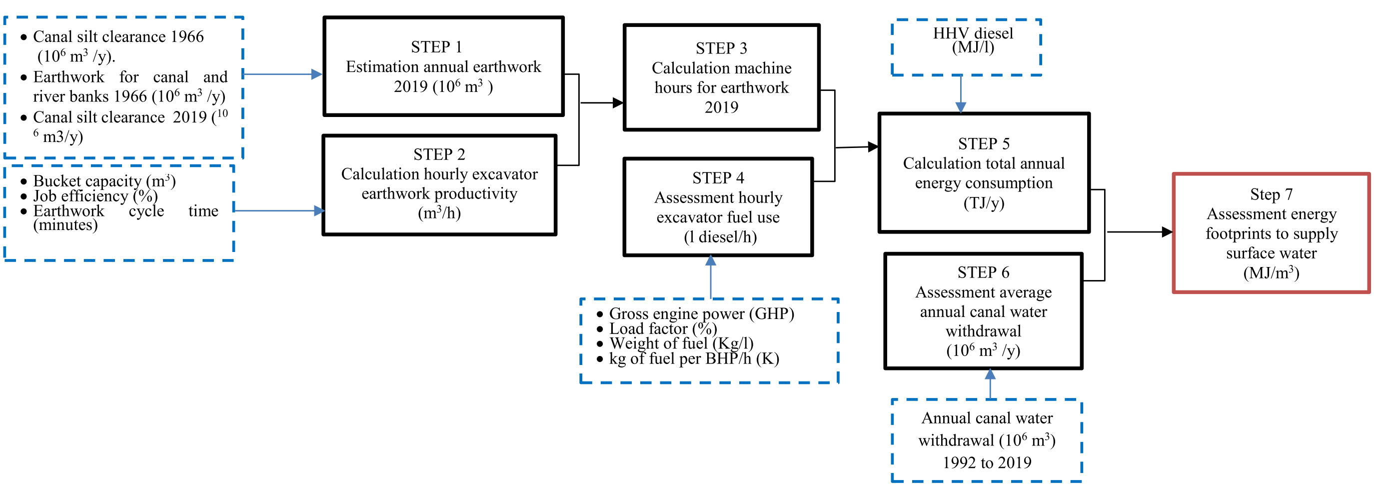

Fig. 2a. Calculation steps for the assessment of operational energy for maintenance of a canal irrigation network to supply surface water in the lower Indus basin in Pakistan till the farm gate.

(i) : Calculation steps of operational energy footprint maintenance of canal network

Step 1. Estimation annual earthwork volume in 2019

Step 1, the estimation of annual earthwork volumes in 2019, was done for two situations: a theoretical situation in which all the silt entering the canal system is removed, and an approach based on actual earthwork volumes from the Sindh Irrigation Department (2019) in Pakistan.

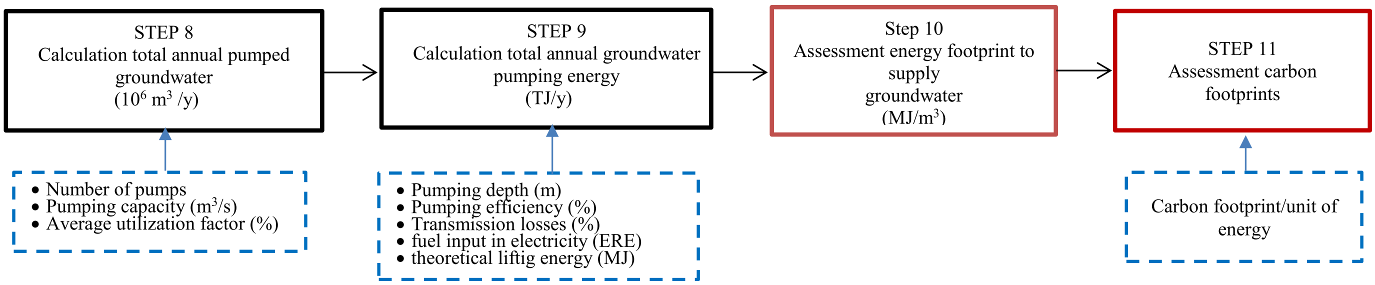

Fig. 2b. Calculation steps for the assessment of operational energy for pumping groundwater in the lower Indus basin (Sindh), Pakistan in 2019 till the farm gate.

3.1. Theoretical approach

The theoretical approach to assess annual earthwork volumes assumes that all silt deposits coming along with irrigation water entering the canal system are removed to keep the canals open so that water can flow from the Indus inlet to the field outlets. Fast flowing water contains more silt than slow flowing water (Havinga et al., 1998). Modeling sedimentation is extremely difficult (Berends et al., 2019), because sedimentation processes are influenced by different factors resulting in different dynamics, e.g. in rivers and its side canals (Van Denderen et al., 2019). We therefore applied a simple sedimentation approach to calculate earthwork volumes and used official earthwork data in combination with energy analysis. To estimate the silt volumes and water amount entering the canal system we assumed that part of the water is lost between inlet and outlet (Habib, 2010). We used the silt gradient difference between the Indus river and the canals to calculate the total annual amount of silt, Vsilt (10^6 kg/y), that needs to be removed as:

$$\text{Vsilt} = \text{Vw x } 1/(1-\text{f}) \text{ x } (\text{siltI}_{\text{ndus}} - \text{silt}_{\text{canal}}) \quad (1)$$

Where, Vw (10^6 m^3/y) is the total average annual amount of water provided by the canal irrigation system between 1991 and 2019, f is the fraction of water lost, $\text{silt}_{\text{Indus}}$ is the silt concentration in the Indus river (kg/m^3) and $\text{silt}_{\text{canal}}$ (kg/m^3) the silt concentration in the canals. Data on Vw were taken from the Indus river system authority (IRSA), and Development statistics of Sindh (2018–2019). For f we assumed a value of 0.5, adopting canal water losses of 50% from Memon et al. (2013). Data on silt concentrations in the Indus of 2.49 kg/m^3 were taken from Liu et al. (2001) and on silt in the canals 0.5 kg/m^3 taken from Vabre (1996).

3.2. Field data approach

The field data approach to assess annual earthwork volumes uses available data on earthwork. For 2019, data on volumes of silt clearance of irrigation canals are available from the Sindh Irrigation Department (2019) (See Table A2 in Appendix 2), but data on volumes for bank strengthening are lacking. There are data on bank strengthening for 1966 though (Mazhar Ali, 1966). Between 1966 and 2019 the silt clearance of the irrigation canals increased by 57%. For the silt volumes to strengthen the banks we assumed the same trend. To estimate the volume of silt for the strengthening of the banks of the irrigation canals and river we assumed a linear relation between volumes of silt clearance and bank strengthening. We calculated the silt volume for the strengthening of canal and riverbanks in 2019, Vsb (2019) by:

$$Vsb\ (2019) = \frac{Vsc(2019)}{Vsc(1966)} \text{ x } Vsb(1966) \quad (2)$$

Where, Vsc (2019) is the volume of silt clearance in 2019, Vsc (1966) the volume in 1966 and Vsb (1966) the silt volume for the strengthening of canal and riverbanks in 1966. Data on silt clearance in 2019 were taken from the Sindh Irrigation Department (2019) and data on silt clearance and earth volumes for the strengthening of canal and river banks in 1966 from Mazhar Ali (1966).

The total required annual earthwork volume (10^6 m^3) in 2019, Vsilt (2019), was calculated as:

$$Vsilt\ (2019) = Vsc(2019) + Vsb(2019) \quad (3)$$

Step 2. Calculation of hourly excavator earthwork productivity

Silt depositing in the canals needs to be removed by machines, i.e. excavators. Silt can be used to strengthen banks or is brought to crop fields. Step 2 calculates the hourly excavator earthwork productivity, Pe (m^3/h). The productivity of an excavator is determined by the volume of soil a machine can displace per unit of time and it depends on the average cycle time, job efficiency and average bucket payload capacity (Caterpillar, 2017). The bucket payload capacity (Cb) is the product of the heaped bucket capacity and the bucket fill factor. The heaped bucket capacity is the total amount of material carried by a bucket, i.e. the amount in the bucket plus the amount piled on top of it. The bucket fill factor depends on the bucket size and soil characteristics. The job efficiency (Ej) depends on machine sizes and job conditions. We calculated excavator productivity, Pe (m^3/hour), as:

$$Pe = \frac{60 \text{ x } Cb}{Tc} \text{ x } Ej \quad (4)$$

In equation (4) the factor 60 was used to convert minutes to hours. Data on Cb, Tc and Ej were taken from the FAO (1992). Table A3 in appendix 2 presents the values.

Step 3. Calculation of machine operation hours for excavator earthwork

Step 3 calculates the total machine operation hours, *Mh* (hours), for excavator earthwork in 2019. We divided the total earthwork volume in 2019, Vsilt (2019), by the hourly productivity per excavator, Pe (m^3/h):

$$Mh = \frac{Vsilt(2019)}{Pe} \quad (5)$$

Step 4. Assessment of hourly excavator fuel use

Step 4 calculates hourly excavator fuel use. According to the FAO (1992), the machine fuel intake rate depends on engine size, load factor, machine condition, operator practice, environmental conditions and machine design. Hourly fuel use depends on the machine application, determining the engine load factor for three machine applications (low, medium and high) and corresponding load factors (%). Earthwork for silt clearance and bank strengthening falls in the medium machine application (Caterpillar, 2017). We adopted the following equation from the FAO (1992) to estimate machine fuel use, LMPH (liters diesel/hour/machine):

$$LMPH = \frac{Kx\ GHPx\ \ LF}{KPL} \tag{6}$$

Where K (kg/h) is the amount of diesel used, GHP, gross horsepower, is the machine power requirement, LF is the load factor (%) and KPL is the standard weight of diesel (kg/l). Data on K, LF and KPL were taken from the FAO (1992) and data on GHP from Caterpillar (2017). See also Table A3 in Appendix 2.

Step 5. Calculation of annual operational energy footprint canal maintenance

Step 5 calculates the annual operational energy footprint for the maintenance of the canal irrigation network in the lower Indus basin in Pakistan, Ec (TJ/y), using the total machine hours and hourly fuel consumption per machine from Step 4 and 5 as:

$$Ec = \frac{(Mh \text{ x } \ LMPH \text{ x } \ HHV) + Etransport}{10\hat{6}} \tag{7}$$

In equation (7) the factor 10^6 is applied to convert MJ (megajoule) to TJ (terajoule), HHV is the higher heating value of diesel of 38.6 MJ/l (The Engineering Tool Box, 2003) and *Etransport* is the energy required to transport the silt to the banks and crop fields. We assumed that the transport distance of the silt is one km. Data on energy for freight, *Efreight*, of 1.7–2.9 MJ/1000 kg/km were taken from Bouwman and Moll (2002). *Etransport* was calculated as:

$$Etransport = Vsilt(2019)\ X\ SWwetsilt\ X\ Efreight \tag{8}$$

Herein *SWwetsilt* is the specific weight of wet silt. We assumed that wet silts contains 50% water, so that *SWwetsilt* is:

$$SWwetsilt = 0.5\ X\ SWsilt + 0.5X\ SWwater \tag{9}$$

Herein *SWsilt* is the specific weight of silt and *SWwater* the specific weight of water of 1 kg/l. Data on the specific weight of sediment (silt) in the lower Indus basin of 1900 kg/m^3 were taken from Farah et al. (1977).

Step 6. Assessment of average annual canal water withdrawal 1992–2019

Step 6 assesses the average annual canal water withdrawal between 1992 and 2019. We calculated the average canal water withdrawal, Vw (10^6 m^3/y), based on 27 years of irrigation water withdrawal from barrages to canals from the Indus river system authority (IRSA), and Development statistics of Sindh (years 1992–2019).

Step 7. Assessment of energy footprint to supply surface water

Step 7 assesses the energy footprint to supply surface water in 2019, Esw (MJ/m^3). For the calculation, we divided total operational energy, Ec (Tj/y), for the maintenance of irrigation infrastructure by the total annual average canal water withdrawal, Vw (10^6 m^3/y), in the lower Indus basin of Pakistan as:

$$Esw = \frac{Ec}{Vw} \tag{10}$$

(ii) : Calculation steps of operational energy footprint to supply groundwater

Step 8. Calculation of annual volume pumped groundwater

Step 8 calculates the annual volume of pumped groundwater in the lower Indus basin in Pakistan where both diesel and electric tube wells are used for groundwater pumping (Qureshi et al., 2003; Pakistan Agricultural Machinery Census, 2004; Bureau of Statistics, Government of Sindh, 2012 and Bureau of Statistics, Government of Sindh, 2018). Groundwater volumes pumped by electric and diesel operated tube wells are calculated separately using corresponding utilization factors, numbers and average discharges (see Table A4 in Appendix 2). We calculated the volume of pumped groundwater in 2019, <u>*Gw* (10^6 m^3/y),</u> as:

$$Gw = \frac{(Pne \text{ x } \ Qe \text{ x } Ufe + Pnd \text{ x } \ Qd \text{ x } \ Ufd)\text{x } (3600 \text{ x } \ 24 \text{ x } 365)}{10\hat{6}} \tag{11}$$

Herein *Pne* and *Pnd* are the number of electric and diesel tube wells, *Qe* and *Qd* are the water discharges of electric and diesel pumps (m^3/s), *Ufe* and *UFd* are the average utilization factors (%), the factor (3600 × 24*365) converts m^3/s to m^3/y and the factor 10^6 is applied to convert m^3 to m^3 10^6. Data on tube well numbers, water discharges and utilization factors were taken from the Development statistics of Sindh from 2011 to 2018; The Groundwater Economy of Pakistan Qureshi et al. (2003); Pakistan Agricultural Machinery Census (2004) and Pakistan Integrated Energy Model (2010).

Step 9. Calculation of total annual groundwater pumping energy footprint

Step 9 calculates the total annual groundwater pumping energy footprint, Ge (TJ/y), for electric and diesel pumps using the equation from Karami et al. (2012) adding the energy required for energy (ERE) value for electricity in Pakistan:

$$Ge = \frac{9.8 \text{ x } \ D \text{ x } \ Gw}{\{OPE\ (1 - T1) \text{ x } \ 1000\} \text{ x } \ ERE} \tag{12}$$

Herein 9.8 is the energy required to lift 1000 m^3 water from 1 m depth at 100% efficiency, D is the groundwater depth (m), OPE is the overall pumping system efficiency (%) and T1 is the transmission loss of electricity (%). Data on pumping efficiencies, average groundwater depth, and efficiencies were taken from (WAPDA, 2009; Qureshi et al., 2003; Qureshi, 2014; Buksh et al., 2000 and ENERCON, 1989) and are summarized in Table A4 in Appendix 2. Data on the efficiency of diesel pumps of 7% was taken from ENERCON (1989). The pumping system efficiency (OPE) of electric pumps of 40% was taken from (ENERCON, 1989; Buksh et al., 2000). Transmission and distribution losses of 25% were taken from (WAPDA, 2009). The ERE value of 2.05 for electricity generation in Pakistan was assessed by multiplying the contribution per power generation type in 2017 by the ERE value for electricity generation. Data on the electricity composition in Pakistan were taken from the IEA (2020), data on ERE values for electricity from the IEA (1999), except for biomass that was adopted from Faaij (2006). See also appendix 1.

Step 10. Assessment of energy footprints to supply groundwater

Step 10 assesses the energy footprint to supply groundwater in

2019, Egw (MJ/m^3). The study divided total operational energy, Ge (TJ/y), for diesel or electric pumps by the total averaged pumped water volume, Gw (10^6 m^3/y), per pump type as:

$$Egw = \frac{Ge}{Gw} \tag{13}$$

Step 11. Assessment of carbon footprints

Energy use, and especially fossil energy use, gives rise to carbon dioxide emissions when fossil fuels are burnt, e.g. oil, natural gas or coal for electricity generation, or diesel to fuel machines (IPCC, 1996). Every country, e.g. Pakistan, has its own fossil fuel mix to generate electricity, depending on the fuels applied (Yousuf et al. (2014). Step 11 assesses the carbon footprints, CF (g/m^3), to supply irrigation water by combining energy footprints with specific carbon dioxide emissions as:

$$CF = Egw \text{ X } CFspecific \tag{14}$$

Herein *CFspecific* is the specific carbon dioxide emission for the fuel applied. Data on specific carbon dioxide emissions for electricity in Pakistan of 0.707 ton per MWh (196.4 g/MJ) were taken from Yousuf et al. (2014) and emissions for diesel of 74.1 ton per TJ (74.1 g/MJ) from the IPCC (1996).

Finally we put our results in perspective. First we made a time trend for annually irrigated areas of surface and groundwater between 1976 and 2016. Data were taken from the Development statistics of Sindh for the period 1992–2019 and from the Agricultural statistics of Pakistan for the years 2015–16.

Irrigation efficiency in the Indus basin includes irrigation efficiency at four levels, at the primary, secondary, and tertiary canals, and field channel and application levels (Ahmad and Majeed, 2001). Second, we assessed water supply per level by combining average annual canal water withdrawal for the period 1976–2016 with specific water efficiencies per level. Data on water withdrawal were taken from the Indus river system authority (IRSA), and Development statistics of Sindh (years 1976–2016). We adopted basin-wide main and branch canals (primary level) efficiencies of 90%, distributaries and minor canals (secondary level) efficiencies of 85% from Azad et al. (2003), watercourses (tertiary level) efficiencies of 70% and field channel and field application level efficiencies of 65% from (Hussain et al., 2011).

Finally, we assessed the groundwater and energy saving potential for seven levels of maintenance expressed by increasing earthwork volumes. We adopted an improvement of water efficiencies due to perfect maintenance of 3–5% from Azad et al. (2003) and next assumed that there is a linear relationship between the volume of earthwork removed and the water saving potential. Lastly we calculated the energy saved related to the improved surface water supply.

4. Results

Fig. 3 shows the volume of annual earthwork to keep the canals open and strengthen the banks in the lower Indus basin in Pakistan for two situations: a theoretical situation where all silt is removed (wet and dry silt) and the actual situation with minimum and maximum silt volumes. It is shown that, based on the theoretical approach using silt concentrations in the Indus, over 200 10^6 m^3 of wet silt needs to be removed per year while actually only 10% of this amount is removed from the canal network.

Fig. 4 shows the energy footprint for maintenance (MJ/t wet silt) for the silt removal phase and for the transportation phase. Silt removal by machines requires about two times as much energy as transporting the silt one km from the canals to the banks or crop fields. The total energy footprint to remove one ton of silt is 6 MJ/t wet silt.

Fig. 5 shows the energy to provide a unit of irrigation water for agriculture (KJ/m^3) from surface or groundwater in the lower Indus basin in Pakistan. There is a large difference between the energy footprint of a unit of surface water, which lies between 3 and 38 kJ/m^3, and the energy footprint of a unit of groundwater with a range of 2100–4000 kJ/m^3 depending on the type of pump used. In general, diesel pumps are more energy-efficient than electric pumps. The figure shows that from an energy perspective groundwater is not a good choice, because the energy footprint is a factor 600 to 1150 larger than the energy footprint of water for the situation in which silt is removed from the canals that provide surface water.

Fig. 6 shows the CO_2 emissions (10^{-6} kg CO_2/m^3) related to energy to provide a unit of irrigation water for agriculture from surface or groundwater in the lower Indus basin in Pakistan. The carbon footprint to provide a unit of surface water for the practical situation varies between 0.22 and 0.30 g CO_2/m^3 and for the theoretical situation the carbon footprint is 2.8 g CO_2/m^3. For groundwater supply, the carbon footprint is 156 g CO_2/m^3 for a diesel pump and 385 g CO_2/m^3 for an electric pump. The figure also shows that the differences between minimum and maximum CO_2 emissions for the practical situation, the theoretical situation and for diesel pumps are the same as for energy footprints shown in Fig. 5. However, CO_2 emissions for electric pumps and diesel pumps vary by a factor of 2.5, whereas the energy footprint of a unit of water pumped by an electric pump is only 1.9 times larger than for a unit of water from a diesel pump. The difference is caused by differences of specific CO_2 emissions of electricity in Pakistan of 196.4 g/MJ (Yousuf et al., 2014) and emissions for diesel of 74.1 g/MJ (IPCC, 1996), in combination with different pumping depths for electric pumps of 60 m and 15 m for diesel pumps.

Fig. 7 shows the annual surface and groundwater water supply for irrigation in the lower Indus basin in Pakistan between 1992 and 2016. The difference between total annual surface water and groundwater supply is enormous. Surface water supply varies between 39 000 and 62 000 10^6 m^3 per year, with an average of 51 000 10^6 m^3. Groundwater supply varies between 2100 and 4200 10^6 m^3 per year with an average of 3300 10^6 m^3 per year. This is only 6% of total annual irrigation water supply in the lower Indus basin in Pakistan.

Fig. 8a–b shows the energy and CO_2 emissions to provide irrigation water from surface or groundwater between 1992 and 2016 in the lower Indus basin in Pakistan. Fig. 8a shows that although the amount of water from groundwater is only 6% of total supply, the energy to provide this groundwater is much larger: 47 times more energy is needed to supply the groundwater than the surface water. Fig. 8b shows a similar trend for CO_2 emissions, but differences between surface and groundwater are larger by a factor of 77 due to the larger specific CO_2 emissions of electricity compared to diesel.

Fig. 9 shows four levels of surface water supply: (i) supply of main and branch canals; (ii) supply of distributary and minor canals; (iii) supply of watercourses and (iv) supply of field channels and field application between 1976 and 2016. It also shows surface and groundwater irrigated areas in the lower Indus basin (Sindh) in Pakistan between 1976 and 2016.

Fig. 9 shows the overall water supply and losses at each level of the canal irrigation system. Conveyance losses are around 50% in the canal network from main to watercourse level. An overall decreasing trend of the canal irrigated area and an increasing trend of the groundwater irrigated area over the last four decades is observed, indicating an increase in groundwater use and a decrease in land irrigated by surface water. Water withdrawals fluctuate

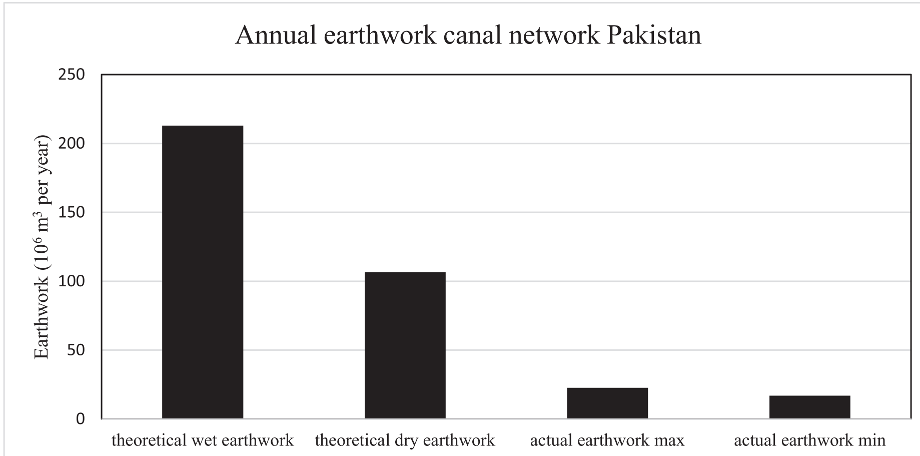

Fig. 3. Volume of annual earthwork to keep canals open and strengthen banks in the lower Indus basin in Pakistan for a theoretical situation where all silt is removed, and for the actual situation with minimum and maximum silt volumes.

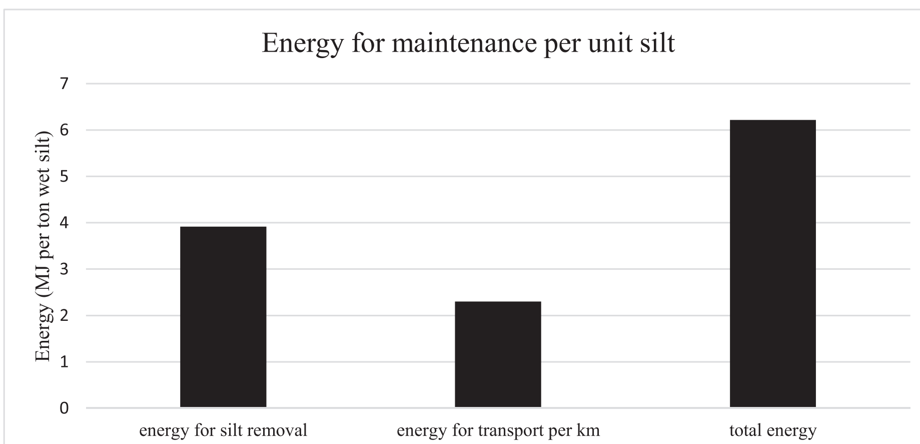

Fig. 4. Energy footprint for maintenance (MJ/t wet silt) for the silt removal phase and for the transportation phase.

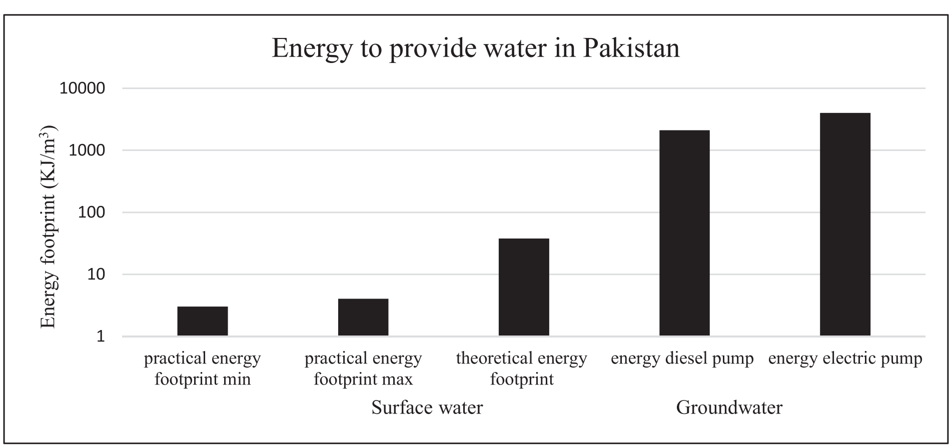

Fig. 5. Energy to provide a unit of irrigation water for agriculture (KJ/m^3) from surface or groundwater in the lower Indus basin in Pakistan (logarithmic scale).

between 42 and 58 10^9 m^3. Only 35% of the surface water, from the primary to the field application level, reaches the crops.

Fig. 10 shows the water and energy saving potential at 3 and 5 percent irrigation efficiency improvement through maintenance of the canal network system in the lower Indus basin in Pakistan.

The study assumed a linear relationship between maintenance (earthwork volumes) and surface water irrigation efficiency improvement based on the assumption that surface water saving potential increases with better maintenance. As a result, the overall energy consumption for irrigation decreases. The surface water

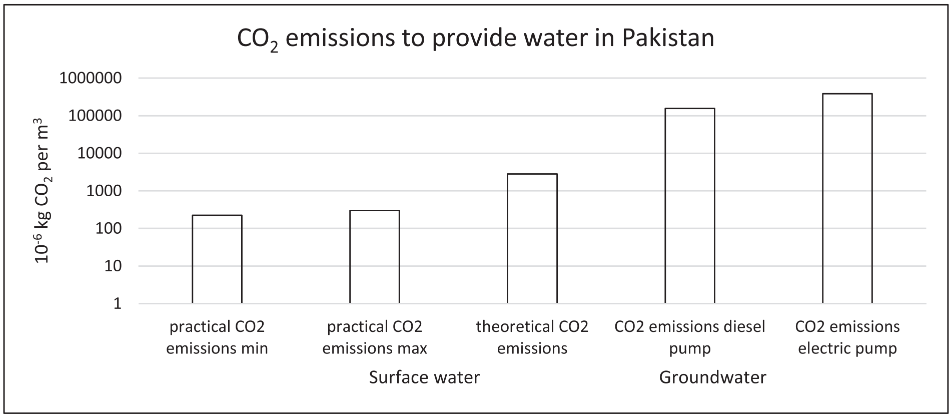

Fig. 6. CO_2 emissions (10^{-6} kg CO_2/m^3) related to energy to provide a unit of irrigation water for agriculture from surface or groundwater in the lower Indus basin in Pakistan (logarithmic scale).

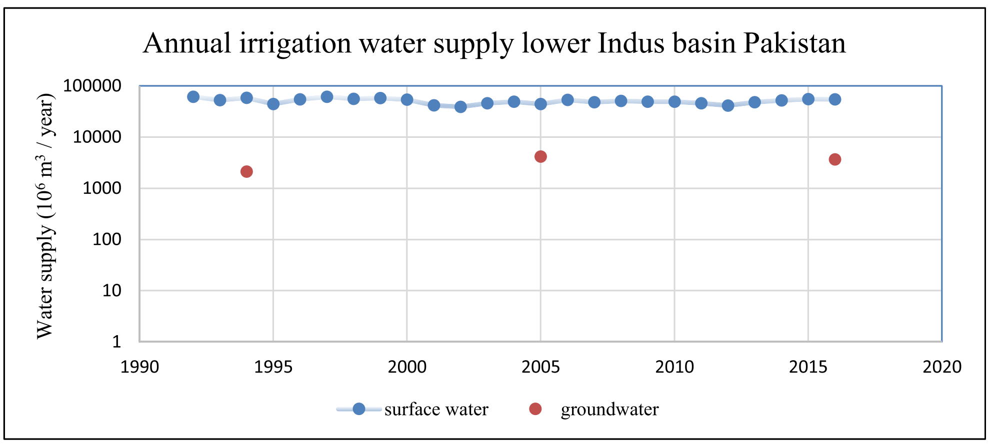

Fig. 7. Annual surface and groundwater water supply for irrigation in the lower Indus basin in Pakistan between 1992 and 2016 (logarithmic scale).

saving potential is enormous, at a 3–5% efficiency improvement level, the water saving can be as large as 3–10% or 1500 to 3000 10^6 m^3, freshwater that does not need to be replaced by groundwater anymore. Energy saving potentials are even larger, in case of perfect maintenance, 31–82% of energy needed to supply irrigation water, or 1537 to 5819 TJ, can be saved.

5. Discussion

Uncertainties can be defined as estimates of the ranges of errors, in other words, they provide information on the ranges of a certain value (Dieck, 2007). There is always a difference between the outcome of a measurement and the precise value. And there are many methods to deal with the difference between the exact and the estimated value (Dieck, 2007). For example, Yung et al. (2019), indicate that it is important to address uncertainties in water-energy-food studies and advise to be clear about assumptions, uncertainties, and data sources of a study and to emphasize that a model is only a tool to better understand a system. Although there are many uncertainties and we had to make assumptions to compare the system to provide irrigation water using a gravity-fed irrigation system and a groundwater pumping system, our comparison shows that from an energy and carbon footprint perspective, a properly maintained gravity-fed irrigation system is to be preferred. We had access to detailed information from governmental organizations in Pakistan which made it possible to perform the analysis on energy for maintenance. We provided the detailed description of the calculations, assumptions and data sources in our method section. This is the most important analysis of the paper, the calculation of groundwater pumping is more straightforward and described often in literature. The availability of the data on maintenance made it possible to make the comparison between energy for maintenance and for groundwater pumping. We emphasize though that our results should not be interpreted at face value, but as tools to compare the systems. We had to make assumptions and encountered uncertainties, however, the difference between the two systems is so large that the final conclusions can be supported. We performed the study for the lower Indus basin in Pakistan where a lot of surface water is lost due to improper maintenance causing farmers to pump groundwater. In other basins situations may be different. However, for our case study better maintenance would be a good solution to improve the situation, although in other basins this could not be a good solution disturbing the water equilibrium causing other ecological and environmental problems. In the following section we discuss the most important assumptions and uncertainties.

5.1. Assumptions and uncertainties

For the assessment of the energy to provide a unit of water till the farm gate in the gravity-fed canal system, the total volume of silt that needs to be removed is an important factor that linearly

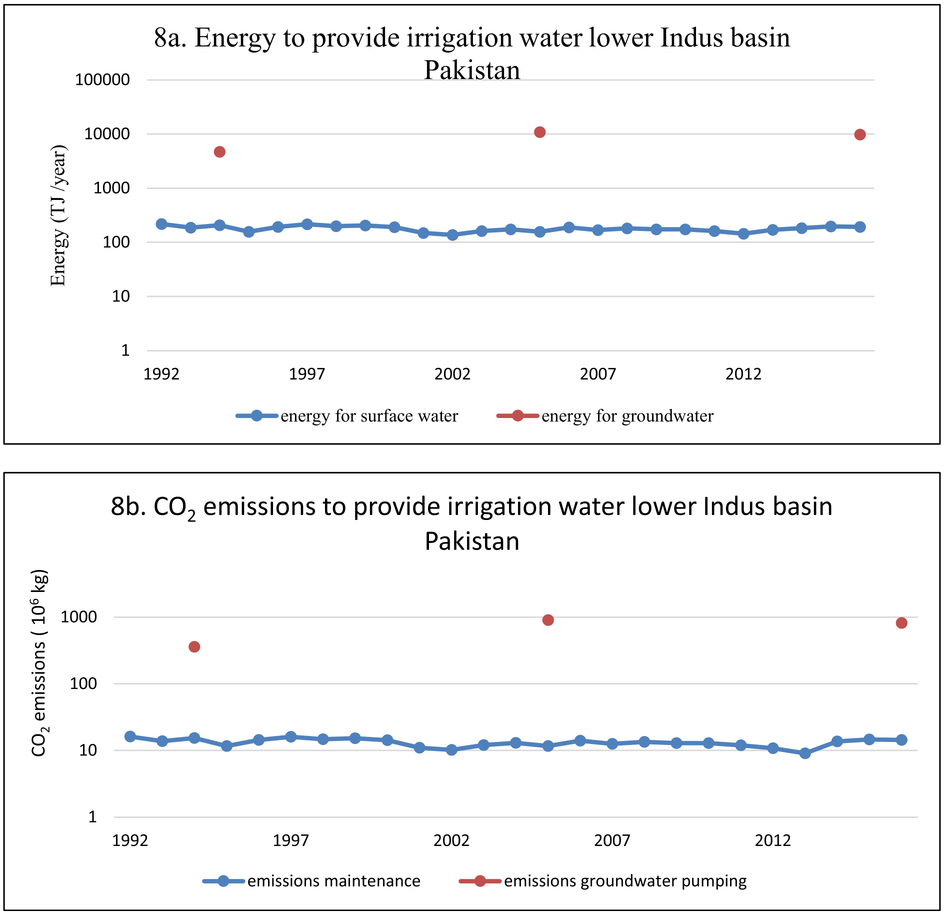

Fig. 8a–b. Energy to provide irrigation water (a) and CO_2 emissions (b) from surface or groundwater between 1992 and 2016 in the lower Indus basin in Pakistan (logarithmic scale).

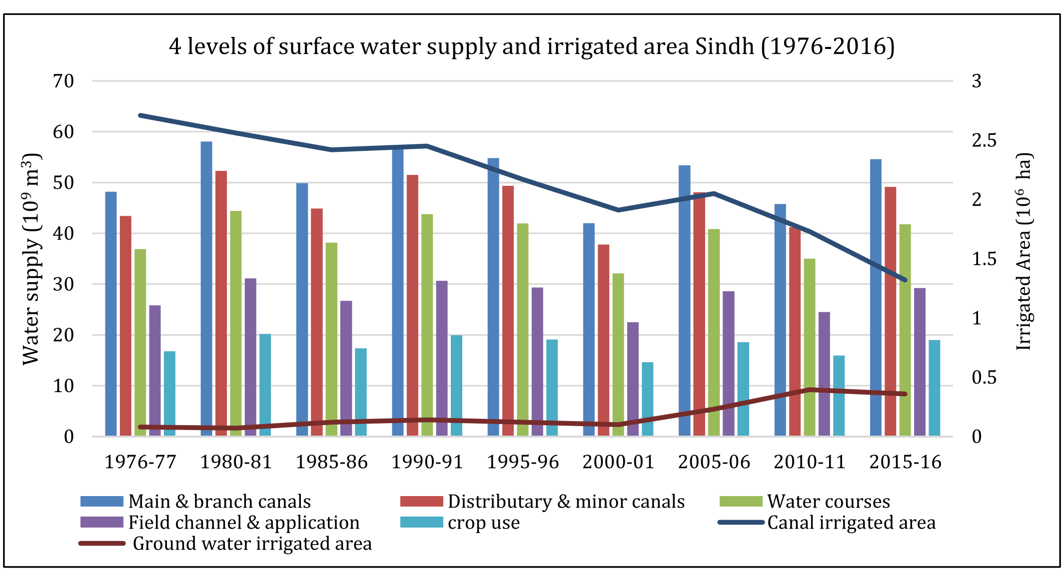

Fig. 9. Four levels of surface water supply (1. Main and branch canals; 2. Distributary and minor canals; 3. Watercourses and 4. Field channel and field application) and surface and groundwater irrigated areas in the lower Indus basin (Sindh) in Pakistan between 1976 and 2016.

relates to total energy use and CO_2 emissions. Although we derived data on the total earthwork volumes for silt removal and bank strengthening from the Sindh Irrigation Department (2019), an official Pakistani government institution, we assumed that it is difficult to exactly assess these volumes. We therefore performed a theoretical assessment on silt volumes that need to be cleared annually assuming a gradient in silt concentrations between the Indus and irrigation water in the canals.

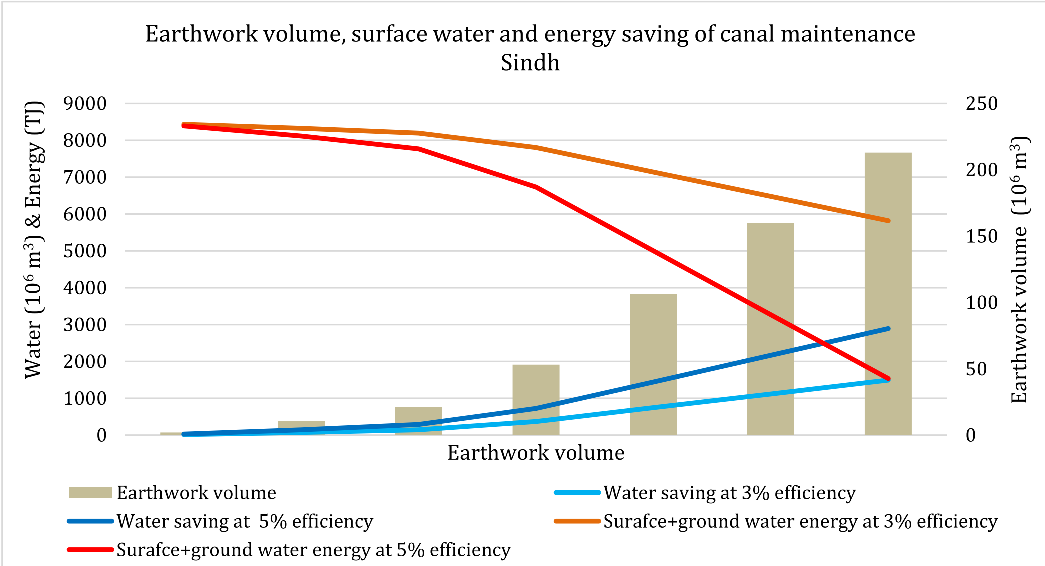

Fig. 10. Earthwork volume, surface water and energy saving potential of canal maintenance, in the lower Indus basin in Pakistan (Sindh) at 3 and 5 percent irrigation efficiency improvement.

Sedimentation is a very complex process (Van Denderen et al., 2019) and difficult to model, but research has shown that also simple models, like detailed models, can explain sedimentation (Berends et al., 2019). Using a simplified approach on concentration differences, our analysis showed that if the canals are maintained in such a way that almost all silt is removed, the canal system providing irrigation water from surface water still has a relatively small energy and carbon footprint. However, our analysis also shows that the annual silt removal from canal networks is only 10% of the theoretical silt concentration, which indicates insufficient maintenance practices in the system. To provide sufficient surface water and to avoid groundwater pumping, a holistic maintenance approach for the long term sustainability of the system is needed in Pakistan.

Another issue is that sediment concentrations in the Indus are uncertain and might change over time. A fifty-year-old study showed that the sediment concentration in the Indus is about 3 kg/m^3 (Holmes, 1968), larger than the value we adopted from a recent study that indicated a concentration of 2.49 kg/m^3 (Liu et al., 2001). In the future, climate change and human impacts will influence water and sedimentation fluxes. Li et al. (2020) have shown that for Asian rivers, like the Indus, water flows and sediment concentrations might decrease, so that the total amount of silt that needs to be removed from the canals also decreases. For the canals we assumed 0.5 kg of silt per m^3 but this value is also uncertain.

For the assessment of the energy footprint and related CO_2 emissions, we took total earthwork volumes for 2019, assuming that earthwork is done by machines. If in some places, manual labor is done, like it was in the past (Mazhar Ali, 1966) we overestimated energy for maintenance. For the theoretical approach, we assumed that the sediments, mainly silt, are wet and contain 50% of water. If the water concentrations are smaller, we overestimated the silt volumes so that they come closer to the actual numbers.

Water withdrawal from the canals is regulated by a system of water rights, so that the Indus river system authority (IRSA), has an overview of these volumes. We assumed an average annual water supply from the canals of 50 848 10^6 m^3/y based on a data range of 27 years, but variation among the years is large. In 1992, 62 000 10^6 m^3 of water was withdrawn, in 2002, 39 000 10^6 m^3. It is uncertain whether the Indus river system authority (IRSA), has a perfect overview of all withdrawal volumes or that also here assumptions were making the data uncertain. Withdrawal volumes have an impact on energy and carbon footprints though, since they are expressed per unit of water. If withdrawal volumes are over- or underestimated, so are the corresponding energy and carbon footprints.

5.2. Comparison with other studies and consequences for policy making

The energy footprint to provide a unit of groundwater was 2.1 MJ/m^3 for a diesel pump (groundwater table 15 m) and 4.0 MJ/m^3 for an electric pump (groundwater table 60 m), including the efficiency loss of a power plant. These values are in line with values from literature. Plappally and Lienhard (2012), for example, estimated energy footprints of groundwater between 0.5 and 5 MJ/m^3 and Frijns et al. (2008) found an energy footprint of 0.4 MJ/m^3, excluding ERE values.

Our results indicated that the energy footprint to provide a unit of surface water due to the maintenance of the Pakistani canals lies between 3 and 4 kJ/m^3. However, there is lack of similar research reported in literature to compare these values. To verify our results, we compared our data with data from a Dutch water board in the North of the Netherlands. The water board uses around 0.664 10^6 L of diesel per year for maintenance using machines to clean 7000 km of ditches (Waterboard Velt en Vecht, 2019). The ditches are about 1 m wide and contain 1 m of water. Energy for maintenance of a ditch in the Netherlands would be around 3.6 kJ/m^3 water. These values are in line within the range of our calculations.

Irrigation water supply in the Sindh province in the lower Indus basin of Pakistan is about one third of total national water withdrawals of 172 10^9 m^3 (Aquastat, 2016). For the whole country, groundwater contributes 34% to total water withdrawal, while irrigation water from groundwater in Sindh is limited because it is brackish and contributes only 6%. Based on our results for energy and carbon footprints of surface and groundwater, the total energy footprint of surface water in Pakistan is about 0.5 10^3 TJ/y, and for groundwater about 200 10^3 TJ/y. Energy for water supply in Pakistan is 4.3% of total energy use of 4354 10^3 TJ/y (IEA, 2020). The total carbon footprint of surface water in Pakistan is about

0.036 10^9 kg/y, and for groundwater about 16 10^9 kg/y or 9% of total CO_2 emissions of 183 10^9 kg/y (IEA, 2020). This contribution is larger than the 1.2% found by Qureshi (2014) who took a larger value for Pakistan's total CO_2 emissions though of 309 adopted from the Pakistan Atomic Energy Commission (2009), while we took the value of 183 MT from the IEA (2020).

The contribution to energy use and CO_2 emissions are completely dominated by groundwater use. Although the contributions of water supply to total energy use and CO_2 emissions are small, they could increase in the future if more groundwater is used. Not only more efficient irrigation systems (Qureshi, 2014) decrease CO_2 emissions, but a shift from groundwater to surface water from properly maintained gravity fed canal network systems could decrease energy use and CO_2 emissions even more.

The decreasing trend of the total irrigated area in the lower Indus basin indicates a severe problem of water logging and salinity due to poor maintenance practices. Inefficiency of the maintenance of the irrigation infrastructure develops tradeoffs towards energy demand for groundwater pumping and decreases fertile land out of irrigation. To provide sufficient surface water and to avoid groundwater pumping, a holistic maintenance approach for the long term sustainability of the system is needed in the lower Indus basin of Pakistan. In the upper Indus basin groundwater contributes around 50% to the irrigation water (Habib, 2010), whereas in the lower Indus basin the share of groundwater is only 4–7%. In the upper Indus basin, conveyance losses in the surface water irrigation network are recovered through groundwater withdrawal at the cost of energy for pumping. However, in the lower Indus basin this equilibrium is not maintained due to natural limitations of the aquifer, which is very saline and poor operation and management practices aggravate the situation even further. Present consequences of poor maintenance are clearly visible and translate in water losses and decreasing areas with surface water irrigation.

5.3. Water-energy food nexus contribution

We emphasize that the concept of the nexus and the interactions of water, energy, food and carbon are very complicated and have many aspects. There is a broad literature on these different aspects, e.g. on water consumption for specific crops, such as a large range of studies on water footprints, water consumption of energy, or the other way around, energy needs of water. However, the nexus is so broad that not all relationships in this nexus are already covered today. There are still many nexus components that are not studied yet. In our paper we tried to include one of these missing topics, i.e. the relationship between energy for freshwater in agriculture, comparing two systems, a system with good maintenance and a system with less maintenance and groundwater pumping. Because conditions differ among specific locations, we took a case study area, the lower Indus basin in Pakistan. We selected this area because it is one of the largest irrigated agricultural areas in the world. Moreover, it is often studied, so data are available. However, there are no existing studies into the differences of energy use to provide the water in this basin. That is what makes the study new so that it covers a knowledge gap in the enormous amount of studies in the water-energy-food nexus. Our approach shows how energy and water can be saved if changes on a system level, including activities on a higher scale level, for which policy is responsible, are taken. This approach is also valuable for other basins and countries.

6. Conclusions

Although we had to make many assumptions and dealt with uncertainties when comparing two irrigation water supply systems in Pakistan, the general trend is clear. Proper canal maintenance in Pakistan providing sufficient surface water avoids groundwater pumping and results in energy, water and carbon savings. From an energy perspective, the gravity-fed canal network system supplying irrigation water performs much better than the groundwater pumping system. Energy for the gravity-fed system is mainly related to earthwork to remove and transport the silt and strengthen the banks, so that the water in the canals keeps flowing. In the lower Indus basin, water supply using the canal system by far exceeds the groundwater supply which is only 6% of total supply. Between 1992 and 2016 the canals provided between 39 000 and 62 000 10^6 m^3/y, with an average of 51 000 10^6 m^3/y, while groundwater supply varied between 2100 and 4200 10^6 m^3/y with an average of 3300 10^6 m^3/y. The water losses from the main canals to the crops are around 65%. If properly maintained, losses decrease so that groundwater is not needed to compensate the water losses. The theoretical approach confirms that there is a lack of maintenance because theoretical silt volumes are far larger than silt volumes that are actually removed.

At present, the energy footprint of a unit of surface water provided by the canal system lies between 3 and 4 kJ/m^3 and the carbon footprint is 0.22–0.30 g/m^3. For a theoretical situation in which all silt is removed, the energy footprint is 38 kJ/m^3 and the carbon footprint is 2.8 g/m^3. These values are small compared to groundwater supply that has an energy footprint of 2100 for diesel pumps to 4000 kJ/m^3 for electric pumps and a carbon footprint of 156 for diesel pumps and 385 g/m^3 for electric pumps respectively.

The total energy footprint of surface water in Pakistan is about 0.5 10^3 TJ/y, and for groundwater about 200 10^3 TJ/y corresponding to 4.3% of total national energy use. The total carbon footprint of surface water in Pakistan is 36 10^6 kg/y and for groundwater about 16 000 10^6 kg/y or 9% of Pakistan's total CO_2 emissions. Groundwater use dominates energy use and CO_2 emissions. In the lower Indus basin in Pakistan, groundwater contributes 6% to agricultural water supply, but carbon footprints are fifty times larger than surface water footprints. Although the contributions of water supply to total energy use and CO_2 emissions are small, they could increase in the future if more groundwater is used. The analysis of an aspect of the water-energy-food nexus indicates that a shift from groundwater to surface water use from properly maintained gravity fed canal network systems in Pakistan could decrease energy use and CO_2 emissions and at the same time improve freshwater supply for agriculture.

There is a clear decreasing trend of areas with surface water irrigation, possibly due to poor canal maintenance and a corresponding increase of areas with groundwater supply. The freshwater and energy saving potential associated with the maintenance of gravity fed irrigation canal systems is impressive. The surface water saving potential at a 3–5% efficiency is 1500–3000 10^6 m^3 or 3–10% freshwater that does not need to be replaced by groundwater anymore. Energy saving potentials are even larger. In case of perfect maintenance, 31–82% of energy needed to supply irrigation water, or 1537 to 5819 TJ, can be saved, thereby also decreasing carbon footprints. The concept of the water-energy-food nexus to assess water, energy (and carbon footprints) in an integrated approach for agriculture producing food, provides new insights into trade-offs and synergies of irrigation systems in the lower Indus basin in Pakistan. Moreover, it gives policy directions of change to improve the system.

CRediT authorship contribution statement

A.W. Siyal: Conceptualization, Data collection and analysis, writing - original draft, preparation. **P.W. Gerbens-Leenes:** writing - review and editing, Contribution to study design. **S. Nonhebel:** visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125489.

Appendix1, calculation ERE value for electricity in Pakistan

To provide a unit of energy, almost always energy is needed. This is the so called energy required for energy (ERE) value. For example, to generate electricity losses take place, and ERE is the inverse of the efficiency of a power plant. Different fuels for electricity have different ERE values (IEA, 1999). We calculated the ERE value for electricity in Pakistan by:

$$ERE = \sum_{i=1}^{n} ERE_{fueln}\ x\ \frac{C_{fueln}}{EL_{total}} \quad (A1)$$

Where ERE_{fueln} is the ERE value (MJ/MJ) of the fuel contributing to the electricity mix, C_{fueln} is the annual contribution of fuel n to the electricity mix (MJ) and EL_{total} is the total annual electricity supply in Pakistan. Data on ERE values were taken from the IEA (1999), except for biomass that were derived from Faaij (2006). The most recent data on electricity supply for 2017 were taken from the IEA (2020). Table A1 gives an overview of electricity supply per fuel, ERE values and the contribution per fuel to the total ERE value.

Table A1
Electricity supply per fuel, ERE values and the contribution per fuel to the total ERE value for electricity in Pakistan in 2017

Fuel	Supply (GWh/y)[a]	Supply (10^6 MJ/y)	ERE (MJ/MJ)	Contribution to ERE
Solar	768	2765	1.08[b]	0.006120
Biofuels	988	3557	1.08[c]	0.027336
Wind	2101	7564	1.08[b]	0.016742
Nuclear	9880	35568	3.38[b]	0.246389
Coal	10911	39280	2.89[b]	0.232654
Oil	29501	106204	2.58[b]	0.561571
Hydropower	32183	115859	1.08[b]	0.256448
Natural gas	49203	177131	1.94[b]	0.704274
Total	135535	487926		2.051535

[a] Source: International Energy Agency (IEA) (2020).
[b] Source: International Energy Agency (IEA) (1999).
[c] Source: Faaij (2006).

The table shows that a total 487 926 106 MJ of electricity is generated in Pakistan in 2017. Thus, using equation A1, the ERE value for electricity in Pakistan is 2.05.

Appendix 2. Additional data sources

Table A2 gives the annual earthwork volumes in 1966 and 2019 from Mazhar Ali (1966) and the Irrigation Department Sindh (2018–19).

Table A2
Annual earthwork volumes in 1966 and 2019

Annual earthwork volumes	1966[1]	2019[2]
Silt clearance from irrigation canals (10^6 m^3/y)	3.54	8.28
Silt for canal and river banks (10^6 m^3/y)	6.37	NA

[1] Mazhar Ali, 1966.
[2] Irrigation Department Bureau of Statistics, Government of Sindh, 2018-19.

Table A3 shows the excavator characteristics for earthwork based on information from Caterpillar (2017) and the FAO (1992).

Table A3
Excavator characteristics for earthwork

excavator characteristic	Code	value
Bucket pay load capacity (m^3)	Cb	0.90[b]
Job efficiency (%)	Ej	0.83[b]
Cycle time (min)	Tc	0.33[b]
Gross engine power (GHP)	GHP	184[a]
Fuel consumption (kg/bhp-h)	K	0.17[b]
Load factor (%)	LF	0.54[b]
Weight of fuel (kg/l)	KPL	0.84[b]

[a] Caterpillar (2017).
[b] FAO (1992).

Table A4 shows the number of installed electric and diesel pumps, the annual utilization factor (annual operation time as a percentage of annual time), pumping discharge, pumping depth, pumping efficiency, and transmission and distribution losses for the years 1995, 2005 and 2016. Data on electric and diesel tube well numbers installed are available for 1995–2005. Data on annually installed tube wells for the period 2005–2010 and for 2011–2016 are available from the Bureau of Statistics, Government of Sindh (2012; 2018). The number of installed tube wells in table A4 is calculated based on the number of installed tube wells in 2005 adding the annually installed number of tube wells from Bureau of Statistics, Government of Sindh (2012; 2018).

Table A4Number of installed electric and diesel pumps, the annual utilization factor (annual operation time as a percentage of annual time), pumping discharge, pumping depth, pumping efficiency, and transmission and distribution losses for the years 1995, 2005 and 2016

Year	Number of pumps	Annual utilization factor	Pumping discharge	Pumping depth	Pumping efficiency	Transmission & distribution losses
		%	m^3/s	m	%	%
Electric						
1995	2993[a]	3.34[a]	0.037[a]	60[e]	40[f]	25[g]
2005	7940[b]	12.00[b]	0.037[a]	60[e]	40[f]	25[g]
2016	8355[d]	11.00[c]	0.037[a]	60e	40[f]	25[g]
Diesel						
1995	25086[a]	9.44[a]	0.027[a]	15[e]	7[f]	
2005	42743[b]	8.42[b]	0.027[a]	15[e]	7[f]	
2016	50924[d]	6.00[c]	0.027[a]	15[e]	7[f]	

[a] Qureshi et al. (2003).
[b] PBoS (2004).
[c] Pak-IE (2010).
[d] Bureau of Statistics, Government of Sindh (2012); 2018.
[e] Qureshi (2014).
[f] ENERCON (1989).
[g] WAPDA (2009).

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