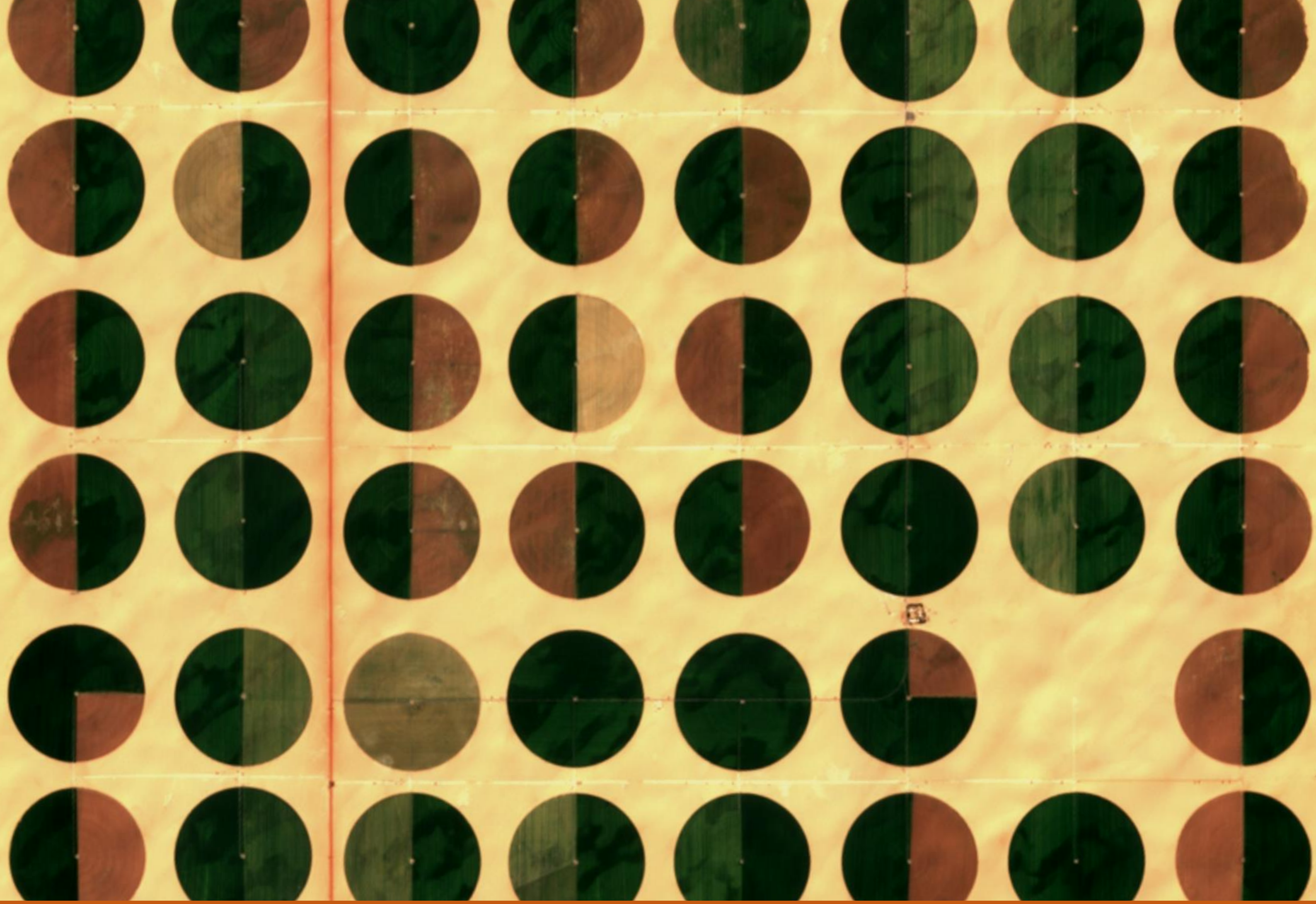

Quantifying the share of non-sustainable groundwater in the blue water footprint of global crop production

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Image on cover page: Central pivot irrigation in East Owainat, Egypt, from EU Copernicus Sentinel-2 L2A satellite product, 1 January 2021, processed with EO browser, true colour. In East Oweinat, non-sustainable groundwater from the Nubian Sandstone Aquifer is used to grow crops. Darker green circles are likely potatoes, light brown circles are expected to be wheat (NASA Earth observatory, 2016).

Preface

What better way to endure a lockdown than graduating? At least, I did not really have a choice in the weird circumstances which 2020 brought me. What I did have a choice in, was the research topic: Global groundwater footprints. All in all, it was intriguing to see large abstract numbers on groundwater abstractions transform in colours and shapes on global maps. These figures have implications. We, as a planet, need to address our overconsumption of groundwater. My study contributes to the scientific field in giving a first global estimate of where how much groundwater is consumed by which crop. Although doing (supposedly) fun and important research, this global water-whodunnit costed me a lot of hard work.

Luckily, supervisors Martijn, Rens and Rick where there to guide me along in how to set up a proper piece of research and how to work with large datasets. Martijn, thanks for your incredible punctuality. Always on time, always answering every question in large detail. Rick, thanks for showing the big picture, especially when got stuck in the details. Although the circumstances never allowed for meeting in real life, Rens, thanks for your enthusiasm and patience in answering dozens of questions on what's under the hood of the PCR-GLOBWB model, and even tweaking the gears of the model over weekends to perform a new model run.

Last, but definitely not least, I'd like to thank the fellow UB-graduate students for nodding politely when I needed to let out some steam, and PhD candidate Oleks, who helped me getting on the way.

Bart Treurniet

Deventer, January 2021

Summary

The agricultural sector is responsible for the largest share in global freshwater consumption, as well as the largest share in non-sustainable groundwater consumption. The consumption of non-sustainable groundwater has adverse affects for the environment, as well as for food security. Detailed information on which crop uses how much non-sustainable groundwater can be used to guide decision making on the sustainable allocation of groundwater. This study concerns the spatial distribution of, and trends in the contribution of groundwater, surface water and desalinated water to the blue water footprint of crops, globally at a high spatial resolution (5x5 arcmin), with a focus on the role of non-sustainable groundwater consumption for crop production. To do so, crop water consumption from the Aqua21 water footprint modelling framework is coupled with consumption from non-sustainable groundwater, sustainable groundwater, surface water and desalination derived from the global hydrological model PCR-GLOBWB. Irrigated area and climate forcing are harmonized in order to combine output data from both models.

The first step in linking both models is to assess the extent to which irrigation withdrawal and consumption from irrigation between Aqua21 and PCR-GLOBWB are in agreement. It was found that both models show the same hotspot areas, but differences in withdrawal and consumption from irrigation are large. Compared to literature, a low consumption from irrigation was found in the used PCR-GLOBWB model run, which is expected to cause an underestimation of the non-sustainable groundwater contribution to the blue water footprint of crops.

The global total blue water consumption over 1981-2010 for all 24 crop types assessed was 816 km^3/yr. The global non-sustainable groundwater consumption equalled 49 km^3/yr (6%). Wheat, rice, maize and cotton are the crops with the largest global non-sustainable groundwater consumption. Date palm and cotton have the largest total blue and non-sustainable groundwater footprints (m^3/ton). India, the USA, and Pakistan account for the largest share of worldwide non-sustainable groundwater consumption. Countries in North Africa and the Middle East have the largest share of non-sustainable groundwater in their water footprint for agriculture.

The global non-sustainable groundwater consumption by crops showed a slight increase over the period between 1981-2010 of 1.0 km^3/yr. This was mainly caused by increases in non-sustainable groundwater consumption by wheat, rice, and cotton. Non-sustainable groundwater footprints decreased for most crop types. Trends in both non-sustainable groundwater and total blue water consumption and footprints were mainly driven by changes in irrigated area and crop yields. Interannual variability was largely caused by variability in blue water consumption due to changes in precipitation and evapotranspiration. Under a growing demand for crops and a changing climate, non-sustainable groundwater consumption and footprints for crops are expected to increase. Non-sustainable groundwater consumption can be reduced by different supply and demand side measures, such as choosing to consume less crops and crop-derived products from areas with non-sustainable groundwater footprints.

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Glossary

Blue water types (or blue water sources) refer to the different categories of blue water: sustainable groundwater (either from irrigation or via capillary rise), non-sustainable groundwater, desalination, and surface water.

Blue water footprints refer to the water footprints of the different types of blue water: The sustainable groundwater footprint, the non-sustainable groundwater footprint, the desalination water footprint and the surface water footprint.

Crop evapotranspiration is the combination of transpiration of water by crops and evaporation from the soil on which crops are grown.

Crop yield is the weight of harvested crop per harvested area.

Irrigated crop yield is the weight of harvested irrigated crop per harvested area equipped for irrigation.

Irrigation water requirement is the quantity of irrigated water which is required to be added to the soil layer for crop production.

Non-sustainable groundwater consumption is consumption or withdrawal of groundwater in excess of long-term recharge.

Return flow is water, which is withdrawn from a source, but not consumed.

Sustainable groundwater consumption is consumption or withdrawal of groundwater less than long-term recharge. Capillary rise is seen as sustainable groundwater consumption.

Water consumption is water removed from a watershed, for example by crop evapotranspiration.

Water footprint is water consumption divided by produced crop weight.

Water withdrawal (or abstraction) is the water removed from a source.

List of symbols

Description	Symbol	Unit
Irrigated area (= area equipped for irrigation)	A_{irr}	m^2 (or ha)
(Crop) water consumption from capillary rise	C_{cr}	m^3/y (or m/y) *
(Crop) water consumption from desalination	C_d	m^3/y (or m/y) *
(Crop) water consumption from irrigation	C_{irr}	m^3/y (or m/y) *
(Crop) water consumption from non-sustainable groundwater	$C_{gw,nonsust}$	m^3/y (or m/y) *
(Crop) water consumption from sustainable groundwater	$C_{gw,sust}$	m^3/y (or m/y) *
(Crop) water consumption from surface water	C_{sw}	m^3/y (or m/y) *
Sectoral consumption by the domestic sector	$C_{sector,dom}$	m^3/yr
Sectoral consumption by the industrial sector	$C_{sector,ind}$	m^3/yr
Sectoral consumption by irrigation	$C_{sector,irr}$	m^3/yr
Sectoral consumption by livestock	$C_{sector,ls}$	m^3/yr
Total sectoral consumption	$C_{sector,tot}$	m^3/yr
Consumption from desalination	$C_{source,d}$	m^3/yr
Consumption from non-sustainable groundwater	$C_{source,gw,nonsust}$	m^3/yr
Consumption from sustainable groundwater	$C_{source,gw,sust}$	m^3/yr
Total consumption from groundwater	$C_{source,gw,tot}$	m^3/yr
Consumption from surface water	$C_{source,sw}$	m^3/yr
Total consumption	$C_{source,tot}$	m^3/yr
Evapotranspiration	ET	m/y
Precipitation	P	m/y
Desalination ratio in consumption from irrigation	R_d	-
Surface water ratio in consumption from irrigation	R_{sw}	-
Non-sustainable groundwater ratio in consumption from irrigation	$R_{gw,nonsust}$	-
Sustainable groundwater consumption ratio in consumption from irrigation	$R_{gw,sust}$	-
Return flow from the industrial sector to surface water	$RF_{ind:sw}$	m^3/yr
Return flow from the domestic sector to surface water	$RF_{dom:sw}$	m^3/yr
Return flow from irrigation to groundwater	$RF_{irr:gw}$	m^3/yr
Withdrawal for the domestic sector	$Wd_{sector,dom}$	m^3/yr
Withdrawal for the industrial sector	$Wd_{sector,ind}$	m^3/yr
Withdrawal for irrigation	$Wd_{sector,irr}$	m^3/y (or m/y) *
Withdrawal for livestock	$Wd_{sector,ls}$	m^3/yr
Total sectoral withdrawal	$Wd_{sector,tot}$	m^3/yr
Withdrawal from desalination	$Wd_{source,d}$	m^3/yr
Withdrawal from non-sustainable groundwater	$Wd_{source,gw,nonsust}$	m^3/yr
Withdrawal from sustainable groundwater	$Wd_{source,gw,sust}$	m^3/yr
Total withdrawal from groundwater	$Wd_{source,gw,tot}$	m^3/yr
Withdrawal from surface water	$Wd_{source,sw}$	m^3/yr
Total withdrawal	$Wd_{source,tot}$	m^3/yr

*Withdrawal for irrigation and different types of crop water consumption are sometimes referred to as a flux in water depth (m/y).

1. Introduction

In this chapter, the background for this study is described, followed by the description of the state-of-the-art in the research field. Then the research gap is set, followed by the research aim and associated research questions. Afterwards, the scope and terminology are determined, and an outline for this study is given.

1.1. Background

Over the past decades, the demand for food has increased, which in its turn led to a rising demand for fresh water to sustain food production (Gleick, 2000). According to Shiklomanov (2000), about 84% of the worldwide freshwater consumption is attributed to agriculture. Fresh water is a scarce resource and may become even scarcer under the influence of a growing water demand and changing climate (Jägermeyr et al., 2016). Fresh water can be stored in surface water and groundwater. When surface water and groundwater, which could be replenished on a short timescale do not meet the water demand for irrigation, non-renewable groundwater is often used by farmers, because it often forms a local, reliable source of water (Aldaya et al., 2009). According to Wada et al. (2012), agriculture accounts for about 85% of global non-sustainable groundwater consumption. Recent studies using hydrological models and remote sensing show that groundwater resources are being increasingly depleted globally (Rodell et al., 2018; Wada et al., 2012, 2014). Groundwater depletion causes groundwater tables to drop and groundwater discharge to surface waters to decline (De Graaf et al., 2019. Groundwater depletion has several negative effects for humans and nature, such as land subsidence, enhancement of hydrological drought and contribution to sea level rise (Bierkens & Wada., 2019). Furthermore, halting or diminishing agricultural production from overexploited groundwater reserves has a negative impact on food security for non-sustainable groundwater consuming countries (Marston et al., 2015; Scanlon et al., 2012).

Water footprint assessment (WFA) can be a useful tool to show the location and quantity of water allocation for production processes, by assessing water use in supply chains (Hoekstra et al., 2011). Mekonnen & Hoekstra (2011) quantified the water footprint of specific crops, as well of consumer end-products derived of crops. Locating and quantifying the consumption of fresh water for crop production can reveal critical hotspots where water consumption exceeds sustainable levels (Hoekstra, 2017b). This information can aid policymakers and companies to decide where and when to grow crops, implement water-saving measures, or where to purchase crops and derived products in order to achieve sustainable crop production or consumption.

In WFA, distinction is made between blue water, which is abstracted from surface water and groundwater, and green water, which consists of precipitation which does not run off or recharge the groundwater (Hoekstra, 2011). Agriculture accounts for a large amount of non-sustainable groundwater consumption. Disaggregating the blue part of the water footprint into non-sustainable groundwater, sustainable groundwater, desalinated water consumption and surface water can reveal the share of non-sustainable groundwater in the blue water footprint of global crop production.

1.2. State of the art

According to Hoekstra (2019), the interest in tracing the origins of water consumed in crop production is increasing. Hoekstra (2019) calls for a 'next step to systematically differentiate between irrigation from fossil versus renewable water resources'. Dalin et al. (2019) argues that virtual water and crop water consumption analysis should distinguish groundwater resources from other water sources given their particular characteristics such as long-term storage and slow renewal times.

The water footprint of crops consists of the water consumed to produce crops and is often expressed in water volume per year, or water volume per unit of produced crop weight. Water consumption in this case refers to water which does not return to a catchment in the form of return flow, which roughly equals evapotranspiration (ET). Crop growth models such as CROPWAT (Allen et al., 1998) and FAO AquaCrop (Steduto et al., 2009) are used in Mekonnen & Hoekstra (2010, 2011) and Hogeboom (2019) respectively to calculate grid-based (30x30 or 5x5 arcminutes) evapotranspiration of water to produce different crops, as well as estimates of crop yields, which are calibrated with national average crop yields provided by FAOSTAT. The challenge at hand is to not only find the evapotranspiration (thus crop water consumption), but also the origin of the consumed water. Evapotranspiration appears in undifferentiated form (Hoekstra. 2019). Chukalla et al. (2015) and Hoekstra (2019) describe how keeping track of the flows into (capillary rise, irrigation, precipitation) and out of a soil (evapotranspiration, runoff, drainage) can be used to find the blue and green parts of ET. Although assessing crop water footprints for a wide range of crop types at a high spatial resolution (such as 5x5 arcmin), Mekonnen & Hoekstra (2010, 2011) and Hogeboom (2019) limit themselves to the soil water balance, without looking at the origin of consumed irrigation water.

Aldaya & Llamas (2008), Aldaya et al. (2009), Zoumides et al. (2013), Dumont et al. (2013), Starr & Levison (2014) and Chouchane et al. (2015) innovated by putting the distinction between the blue surface water footprint and the blue groundwater footprint into practice. These studies made use of local available data on groundwater abstractions and/or agricultural areas which are irrigated by groundwater to underpin their conclusions on the blue groundwater footprint on a regional scale. On a global scale however, obtaining reliable estimates of groundwater withdrawal and consumption remains difficult (Esnault et al., 2014).

The use of (global) hydrological models can be helpful in this regard. Models such as LPJML (Rost et al., 2008), PCR-GLOBWB (Dalin et al., 2017; Wada et al., 2012, 2014), H08 (Hanasaki et al. (2010, 2018), WaterGap (Döll et al., 2012, 2014) and WBMPlus (Wisser et al., 2010) include estimates on the origin of irrigation water, be it from non-sustainable groundwater, sustainable groundwater, surface water, desalination, or non-local sources. However, most of these studies aim at finding the impact of irrigation for the entire agricultural sector on water sources such as surface water and groundwater, rather than attributing the use of water to specific crop types, which is important in water footprint accounting. Furthermore, as these studies are focussing solely on hydrology, rather than on water footprint accounting, produced crop weight is not simulated.

The combination of using hydrological models including groundwater withdrawal for irrigation and linking groundwater withdrawal to crop yield is present in the work of Hanasaki et al. (2010), Hanasaki (2016), Dalin et al. (2017), Bierkens et al. (2019), and Grogan et al. (2015). Grogan et al. (2015) calculates crop yields with a crop-growth model on a 0.5x0.5 arc degree grid within China but does not disaggregate the water footprints found per crop type. Hanasaki et al. (2010) and Hanasaki (2016) use a crop-growth module within the H08 global hydrological model to calculate crop yields for four main crops globally. Bierkens et al. (2019) calculates the contribution of different three different water sources (green, non-sustainable groundwater, blue water excl. non-sustainable groundwater) to the blue virtual water content of 5 crop types for the most important groundwater-depleting countries and uses national yield statistics. Dalin et al. (2017) uses national statistics on crop yields as well and reports only groundwater depletion per crop yield on a national scale for several crop types, globally. Dalin et al. (2017) links the groundwater depletion found for crop consumption to a global trade analysis, in order to gain insight in the way consumption patterns lead to groundwater depletion elsewhere.

Although a large body of literature has developed on water footprints of different crops on different geographical scales, few studies focus on temporal variability of water footprints. Focussing on several geographical extents in China, Sun et al. (2013a, 2013b) and Zhuo et al. (2014, 2016a, 2016b) show that temporal changes in blue and green water footprints are to a large extent the consequence of a changes in crop productivity, and somewhat less to changes in climatic conditions. Furthermore, blue water footprints are more sensitive to changes in actual evapotranspiration than green water footprints (Zhuo et al., 2014, 2016a). On a global scale, Tuninetti et al. (2015) and Hanasaki (2016) show the same pattern, but also highlight regional variability. Zoumides et al. (2013) showed for Cyprus that the groundwater consumption for crop production in the driest year was 37% higher than the wettest year in the record.

In order to be useful as a guidance for policymakers, producers and consumers of crops and crop-derived products, a blue groundwater footprint assessment for crops can benefit from including a large number of crop types at a high spatial resolution, in order to provide detailed insights on the sustainability of produced foods regarding water use (Dalin et al., 2019). Furthermore, keeping track of temporal developments in crop-related blue groundwater footprints is important to understand how human pressure on the different sources of blue water develops (Dalin et al., 2017; Zhuo et al., 2016b).

1.3. Research gap

Based on the review of state-of-the-art literature in the fields of global hydrological modelling and water footprint assessment, the following research gap is defined:

On a global scale, at a high spatial resolution (such as 5x5 arcmin), no study has been presented yet which calculates the contribution of different sources of water (non-sustainable groundwater sustainable groundwater, surface water, desalination) to the blue water footprint (in water volume per produced crop weight), specified for different crop types, and calculates the relative non-sustainable groundwater contribution to the total blue water footprint per crop type, both with respect to spatial variability, as well as temporal development.

1.4. Research aim

The objective for this research is to quantify the spatial distribution of, and trends in the contribution of groundwater, surface water and desalinated water to the blue water footprint of crops, globally at a high spatial resolution (5x5 arcmin), with a focus on the role of non-sustainable groundwater consumption for crop production.

1.5. Research questions

The following research questions are posed to fulfil the research aim:

1. To what extent is long-term average irrigation water withdrawal and consumption from irrigation in PCR-GLOBWB and Aqua21 in agreement?

2. What is the spatial distribution of the contribution of surface water, desalinated water, sustainable groundwater, and non-sustainable groundwater to the blue water footprint of crops for a long-term average at a global scale on a 5x5 arcmin resolution, and what is the contribution of different crops to non-sustainable groundwater consumption?

3. Which long-term trends and interannual variability in the total and relative contribution of non-sustainable groundwater to the blue water footprint can be observed?

1.6. Scope

Although the spatial scope entails the entire globe, this research is restricted in other aspects. Finding a long-term average is restricted to the period between 1981 and 2010, as this entails the most recent 30-year period for which input data is available. The 30-year window is chosen, as 30 year represent a climate cycle (World Meteorological Organisation [WMO] ,2019). For the temporal variability, data between 1981 and 2010 is used as well.

Agriculture accounts for the largest contribution to unsustainable groundwater consumption worldwide (Wada et al., 2012). This research therefore focusses on agriculture. More specifically, to the production of crops. Secondary products, end-products and water-consuming processes associated with agriculture, other than irrigation and water conveyance for irrigation are left out of consideration. Although particularly interesting for follow-up research, the virtual (non-sustainable) groundwater trade of crops and derived products is not addressed here either. Crop production does not only appropriate groundwater in terms of physical consumption, but also by pollution (Karandish et al., 2018), which can be quantified using the grey water footprint (Hoekstra et al., 2011). This research does not take appropriation of groundwater by pollution into consideration.

On a global scale, crop-growth models are commonly used to find information on blue and green crop water consumption and crop yields on a high resolution grid, while global hydrological models can determine the source of water used for irrigation. Output data from the integrated water footprint modelling framework Aqua21, which makes use of the AquaCrop crop growth model (Hogeboom, 2019; Hogeboom et al., 2020, unpublished) is used to assess crop water consumption and crop yields for its ability to model many crop types at a high spatial resolution. According to Hogeboom et al. (2020, unpublished), using a crop growth model increases accuracy in comparison to using only a soil water balance. The hydrological model PCR-GLOBWB has shown its value in assessing groundwater consumption for irrigation on a global scale at a high resolution in Wada et al. (2012, 2014), Dalin et al. (2017) and Bierkens et al. (2019) and is used to trace the origins of irrigation water abstractions. Output data from PCR-GLOBWB on the share of non-sustainable groundwater, sustainable groundwater, desalinated water, and surface water in irrigation water consumption is matched to blue water consumption and crop yield in Aqua21. This is done instead of fully integrating both models in which irrigation water demand in Aqua21 directly affects water availability in PCR-GLOBWB during each modelling timestep (usually daily), and vice versa.

1.7. Terminology

For a clear understanding of the methods and results in this research, the terminology used in this research is described below.

1.7.1. On the sustainability of groundwater consumption

When it comes to sustainability of groundwater, several definitions are often used in the field. For a thorough literature review, I refer to Bierkens & Wada (2019) and Gleeson et al. (2020). According to Bierkens & Wada (2019), the terms 'fossil groundwater', 'non-renewable groundwater', 'non-sustainable groundwater use' and 'depletion' are often used interchangeably, while they are not entirely the same. Fossil groundwater refers to groundwater that is recharged long ago (for example before the Holocene). Bierkens & Wada (2019) define non-renewable groundwater as groundwater with mean renewal times surpassing human time scales (>100 years), based on Margat et al. (2006). Groundwater depletion, or non-sustainable groundwater withdrawal refers to "Prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities exceeding average annual replenishment, leading to a persistent decline in groundwater levels and reduction of groundwater volumes" (Bierkens & Wada, 2019, based on Margat et al., 2006). Thus, according to this definition, groundwater depletion can occur in aquifers with both renewable and non-renewable groundwater resources. Gleeson et al. (2020) proposes a more holistic definition of non-sustainable groundwater, including notions of inclusive, equitable and long-term governance and management. However, in modelling practices often a narrow physical definition is used, such as in Wada et al. (2012). Here, depletion and non-sustainable groundwater consumption are used interchangeably, referring to the part of the withdrawn groundwater in excess of the inflow into groundwater by recharge and riverbed infiltration, leading to permanent loss of groundwater from storage, based on Sutanudjaja et al. (2018). In this research 'sustainable groundwater consumption' thus refers to all groundwater consumption which is not in excess of the inflow into groundwater by recharge and riverbed infiltration.

1.7.2. Abstraction, withdrawal, consumption, and irrigation water requirement

In line with Hoekstra et al. (2011), water consumption or water use refers to the definitive removal of water from a watershed. In the case of crops, this comes down to evaporation from the soil crops are grown on, and transpiration by crops. The terms abstraction and withdrawal are used interchangeably in this report for retrieving water from a source of water, such as surface water or groundwater. A part of this can be consumed, while a part can flow back as a return flow, for example in the case of irrigation losses. Irrigation water requirement is the water needed to be added to a soil in order to sustain normal crop growth. This is not entirely the same as crop water consumption, as water in the soil could also percolate to deeper layers, instead of being consumed by crops.

1.7.3. The unit of the water footprint

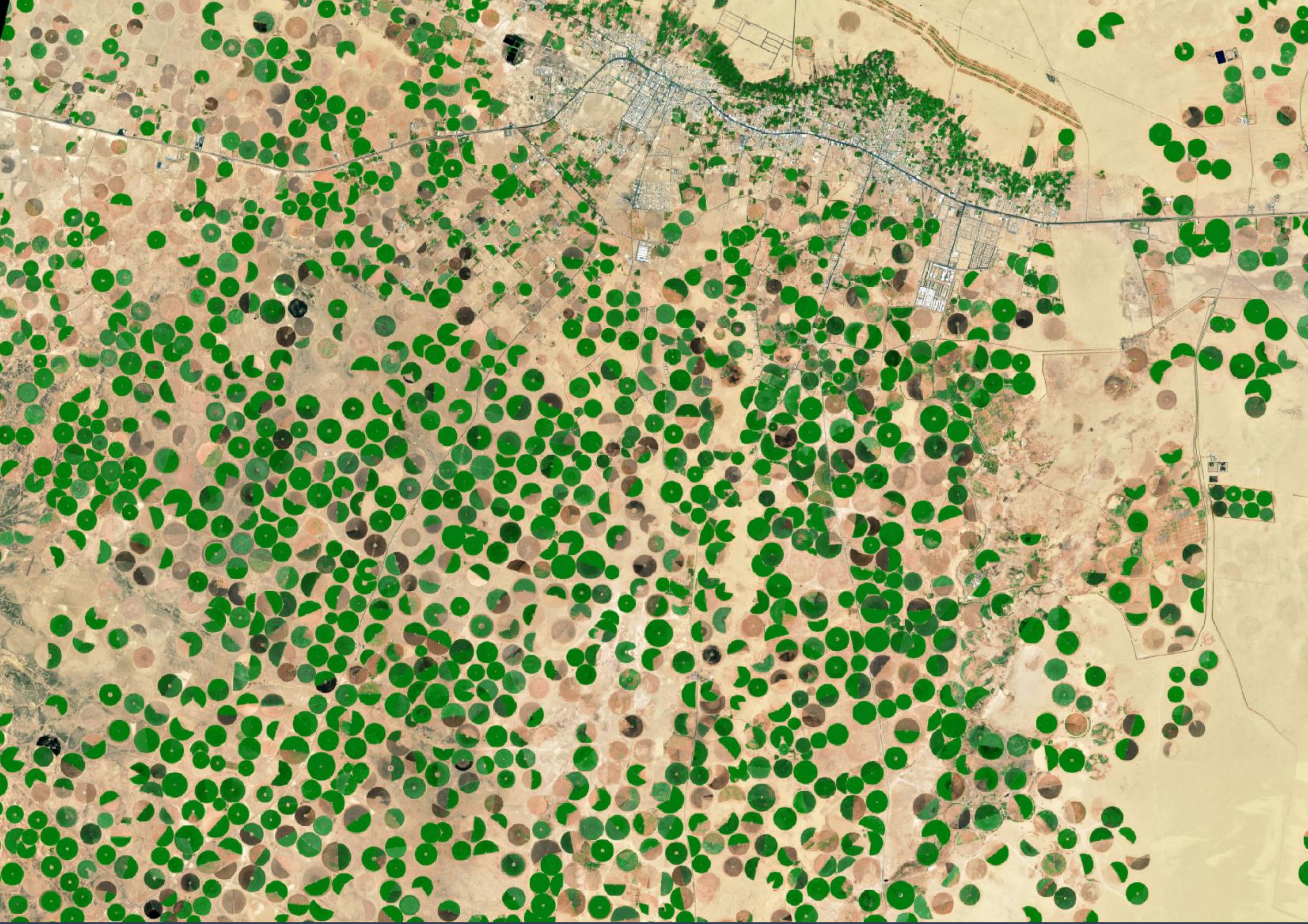
According to Hoekstra et al. (2011), water footprints can be denoted in different kinds of units, such as volume over time, volume over price (see for example Aldaya et al., 2009) or volume over weight. When referring to a water footprint, the latter is used in this study.

1.7.4. The different types of the blue water footprint

Water consumed by crops can be withdrawn from surface water, desalination, sustainable groundwater, and non-sustainable groundwater, which are referred to as the sources of blue water. The water footprint of water from these sources is referred to as the different types of the blue water footprint, or the different blue water footprints. In the remainder of this document, the 'contribution of non-sustainable groundwater to the blue water footprint of crops' is shortened to 'the non-sustainable groundwater footprint', in line with Karandish et al. (2018). This definition should not be confused with the groundwater footprint introduced by Gleeson et al. (2012). They defined the groundwater footprint as the area required to sustain groundwater use and groundwater-dependent ecosystem services. Although the methodology to attain the groundwater footprint is complementary with water footprint calculations (Gleeson et al., 2012), the groundwater footprint focusses on the ratio of available groundwater and used groundwater for human and ecosystem purposes and the impact of groundwater use on aquifers, rather than quantifying the groundwater volumes used for products and processes in water footprint assessment.

1.8. Outline

The outline of this study on the quantification of the share of non-sustainable groundwater in the blue water footprint of global crop production is as follows: Chapter 2 describes the methods used to compare PCR-GLOBWB and Aqua21 and calculate the share of non-sustainable groundwater in the blue water footprint. Chapter 3 shows the results per research question. In chapter 4, the findings in this study are discussed. In chapter 5, conclusions and recommendations for further research are given.



2. Methodology

2. Methodology

In this chapter, the methods used to answer the posed research questions are discussed.

2.1. General approach

Within the Aqua21 water footprint modelling framework, crop growth model AquaCrop is used to simulate crop water use and crop yields for different crop types on a 5x5 arcminute grid with global coverage for the period 1981-2010. Using the water balance method of Chukalla et al. (2015), evapotranspiration is traced back to the sources: irrigation, capillary rise, and precipitation (Hogeboom, 2019). Here, blue water from irrigation is traced further back and subdivided into surface water, desalinated water, non-sustainable groundwater, and sustainable groundwater using PCR-GLOBWB, see Figure 1. Sustainable groundwater reaches the root zone of crops by either capillary rise, or via groundwater withdrawal for irrigation. For simplicity purposes, capillary rise is included in sustainable groundwater, although in reality, this is not strictly always the case.

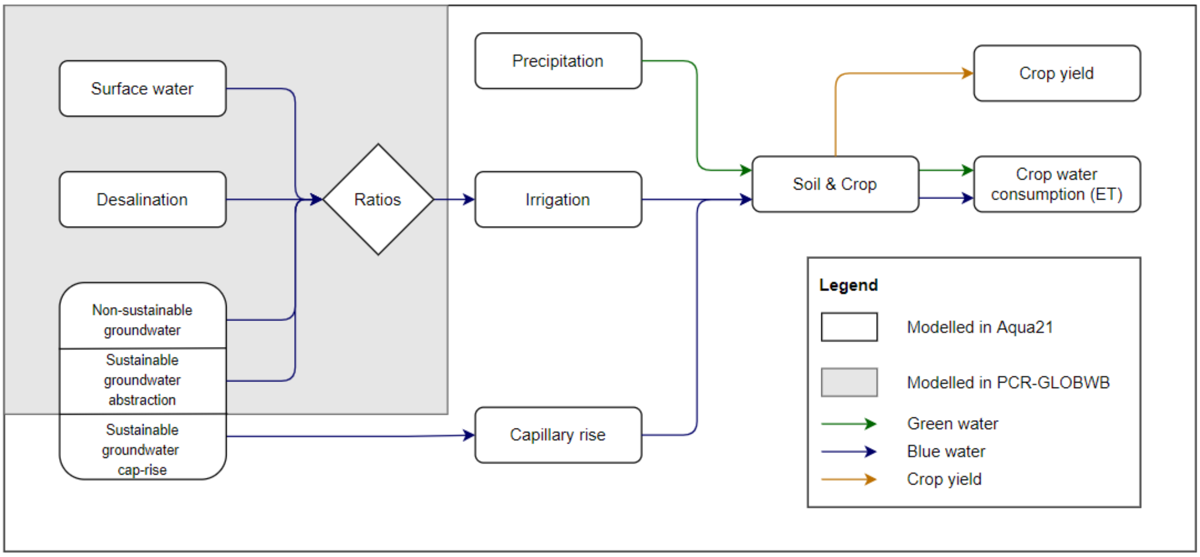


Figure 1 – Conceptualisation of the use of the models Aqua21 and PCR-GLOBWB in this study.

In order to use results on the contribution of non-sustainable groundwater, sustainable groundwater, desalinated water, and surface water to the blue water footprint of crops, it is important to see whether the quantities of irrigation water demand and consumption in both models are similar. In research question 1, the irrigation withdrawal and consumption for both models are compared. In the methodology section for this research question, the harmonization of model inputs is described, as well as the method to compare both models. Afterwards, for research question 2, the ratio of each source of irrigation water calculated with PCR-GLOBWB is applied to the consumption from irrigation water in Aqua21 and combined with water consumption from capillary rise to find long-term average non-sustainable groundwater, sustainable groundwater, desalination and surface water consumption and footprints. Finally, the methods used to assess long-term trends and interannual variability in the different types of the blue water consumption and footprints are described.

2.2. Differences in irrigation withdrawal and consumption from irrigation between both models

In answering research question 1 on the differences in irrigation withdrawal and consumption from irrigation between PCR-GLOBWB and Aqua21, first a brief overview of PCR-GLOBWB and Aqua21 is given. Then, relevant model inputs are harmonized. Afterwards, the differences in irrigation withdrawal and consumption from irrigation are assessed.

2.2.1. Comparison between PCR-GLOBWB and Aqua21

Before harmonising PCR-GLOBWB and comparing withdrawal and consumption from irrigation in both models, a brief overview is given of the relevant model structures in PCR-GLOBWB and Aqua21. For an elaborate description on how both models calculate crop water consumption, irrigation water demand and the allocation of groundwater, see Appendix A. More information on Aqua21 can be found in Hogeboom et al. (2020, unpublished), and Raes (2017) for the structure of the underlying AquaCrop model. Up-to-date descriptions of the newest versions of PCR-GLOBWB, which is used for the model run in this study, can be found in Sutanudjaja et al. (2018) and Hofste et al. (2019).

Essentially, Aqua21 is a combination of a crop growth model and a soil water balance which calculates crop water consumption. In Aqua21, distinction is made between consumption from green water and blue water. Using the state-of-the-art crop growth module AquaCrop, crop canopy growth is dynamically calculated, from which crop yield and crop water consumption is derived. Global hydrological model PCR-GLOBWB calculates crop water consumption as well using a simpler fixed parameterisation. Other water fluxes in the global terrestrial part of the water cycle are included as well, such as water withdrawal for non-irrigation purposes and groundwater abstraction, among others. In Aqua21, 59 crops are modelled. In PCR-GLOBWB, only three overarching crop classes exist: irrigated paddy (rice), irrigated non-paddy and rainfed. The relevant model components and inputs for this study in Aqua21 and PCR-GLOBWB are shown and compared below using Figure 2 as a basis.

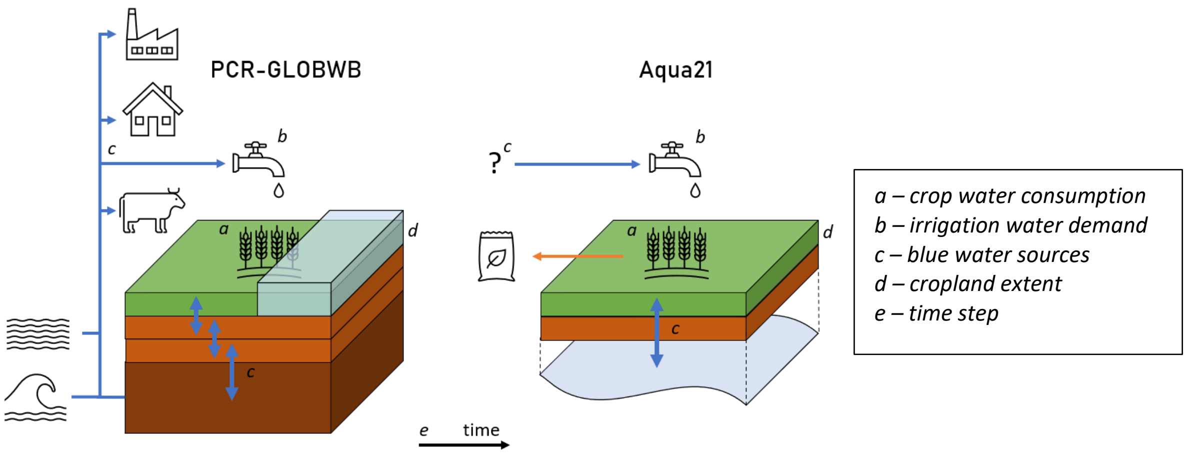


Figure 2 – Simplified representation of relevant model components and inputs.

a) Crop water consumption

In PCR-GLOBWB, crop water consumption is calculated solely using a fixed parameterisation by Allen et al. (1998), based on reference evapotranspiration and crop coefficients by Siebert & Döll (2010) during a certain stage in the growing season. Growing seasons are defined using the cropping calendar provided by Portmann et al. (2010). Aqua21 takes the cropping calendars by Portmann et al. (2010) as a basis as well, extended with cropping calendars for minor crops by Monfreda et al. (2008). In Aqua21, crop coefficients are proportional to dynamically modelled canopy growth (Raes, 2017). Furthermore, crop water demand is a function of more factors, including stress factors such as drought, but also management practices. In PCR-GLOBWB, harvest dates are fixed, while in Aqua21, crops are harvested based on the dynamically calculated crop development stage.

b) Irrigation water requirement

In PCR-GLOBWB, paddy and non-paddy irrigation water requirement are calculated differently. For paddy rice, a 50 millimetre surface water depth is maintained until the late crop development stage. For non-paddy crops in PCR-GLOBWB, as well as all crops in Aqua21, irrigation is applied when the soil water in the root zone falls below a certain value. This value is set different in both models. In Aqua21, irrigation up to field capacity is applied when readily available water in the soil is depleted more than 30%. In PCR-GLOBWB, irrigation up to field capacity is applied when readily available water falls below a dynamic threshold based on total available water and a factor which is a function of crop evapotranspiration and a reference soil water depletion faction (Wada et al., 2014).

c) Blue water sources

In Aqua21, crop evapotranspiration is traced back to a precipitation and two blue water sources: Irrigation and capillary rise. In PCR-GLOBWB, no such tracing is included, which makes it impossible to assess the blue evapotranspiration coming from capillary rise. AquaCrop uses a fixed water table as input in order to calculate deep percolation and capillary rise. In Aqua21, the global equilibrium depth groundwater map by Fan et al. (2013) at a 0.25 degree resolution is used for this variable. In PCR-GLOBWB, deep percolation and capillary rise are calculated dynamically. In PCR-GLOBWB, irrigation water is dynamically attributed to desalination, sustainable groundwater, non-sustainable groundwater, or surface water (see Appendix A).

d) Cropland extent

Irrigated and rainfed cropland extent for main crop types in Aqua21 are derived from the MIRCA-database by Portmann et al. (2010), who established a global 5x5arcminute representative database for around the year 2000. Minor crops are used from the database provided by Monfreda et al. (2008) which covers the year 2000 as well at a 5x5 arcminute resolution. For other years than the year 2000, the Monfreda/Portmann base map is masked by the irrigated cropland extent from HYDE3.1 (Klein Goldewijk et al., 2011) and HID (Siebert et al., 2015). When according to these historical masks agricultural land is not irrigated, it is set to rainfed (Schyns, personal communication, October 12, 2020). Finally, FAOSTAT annual reported values for harvested area (rainfed and irrigated combined) (Food and Agriculture Organization of the United Nations [FAO], 2020) are used to scale the 5x5-arcminute grid based values in such a way that they match national total harvested areas. The datasets by Portmann et al. (2010) and Monfreda et al. (2008) include cropping calendars with crop factors which take multicropping into account. In Aqua21, multiple sub-crops of the same main-crop in MIRCA2000 (such as spring wheat for main crop wheat) which use different growing areas and crop parameters are allowed to grow in the same year in the same grid-cell. PCR-GLOBWB takes three agricultural land cover variables as input: Irrigated paddy area, Irrigated non-paddy area and rainfed area. These areas stay constant within a year. Crop calendars with crop coefficients from Siebert & Döll (2010) are used from the crops in the MIRCA-database for the year 2000, except for the classes ‘fodder grasses’ and ‘others annual’. Crop coefficients for the crop types ‘irrigated paddy’, ‘irrigated non-paddy’ and ‘rainfed’ are found by weighing the MIRCA-crop coefficients from the MIRCA-crops within these crop types with their relative area for each grid-cell (Wada et al., 2014).

e) Time step

The results in Aqua21 are reported per month or for the aggregated days within a growing season of a crop. A growing season extents from germination to sowing. In PCR-GLOBWB, results are reported on a monthly or annual basis. Linking consumption from water from sources from PCR-GLOBWB to water consumption in Aqua21, this may cause small discrepancies.

2.2.2. Harmonisation

It is important to harmonize model inputs between Aqua21 and PCR-GLOBWB. According to Sun et al. (2013a), Zhuo et al. (2014) and Tuninetti et al. (2015), crop water consumption calculations following the calculation method by Allen et al. (1998) are most sensitive to the variables of reference evapotranspiration, crop coefficients and planting dates and length of growing season. Available water content, which is determined by the type of soil played a less important role (Tuninetti et al., 2015; Zhuo et al., 2014). The global irrigated water demand is expected to be sensitive to irrigated area as well, based on simulations with global hydrological model WBMplus (Wisser et al., 2008) and PCR-GLOBWB (Bosmans et al., 2017). Hence the need to harmonise climate forcings, as well as irrigated cropland extent. Because PCR-GLOBWB is more flexible to run than Aqua21, it is chosen to rerun PCR-GLOBWB with similar input variables for climate and irrigated cropland extent as the available Aqua21-run by Hogeboom (2019). Planting dates are in both models obtained from Portmann et al. (2010). Growing season lengths and crop coefficients are not possible to align, due to the different model structures. Because PCR-GLOBWB only uses crop coefficients of 24 MIRCA-crops, in this study, the different types of the blue water consumption and footprint is determined for these 24 crop types as well, instead of for the 59 crop types included in Aqua21 (see Appendix B).

To harmonise both models, the following steps are taken: First, monthly growing areas per crop in Aqua21 are averaged to find average growing areas per year. Then, all the annual average growing areas of Aqua21-crop types which do not belong to the MIRCA-classes ‘fodder grasses’ and ‘others annual’ are aggregated into the classes ‘irrigated non-paddy’, ‘irrigated paddy’ and ‘rainfed’. Due to the masking and scaling procedures used in Aqua21, it does sometimes occur that the total annual irrigated area exceeds the total available grid-cell area for irrigation (other area may be occupied by freshwater reservoirs, or tall natural vegetation) for a part of the grid-cells in some years. In these cases, the rainfed area is capped. When the total available area is still exceeded by then, irrigated non-paddy and irrigated paddy areas are capped as well. The maximum annual area, which is excluded by capping, is 0.2% of the total irrigated area in that year. For a complete overview of the crop types involved in the databases by Portmann et al. (2010), Monfreda et al. (2008), Aqua21 and the used PCR-GLOBWB run and the way they are aggregated, see Appendix B. Crop coefficients in PCR-GLOBWB remain unaltered and represent the weighted average composition of MIRCA-crops instead of the harmonised Aqua21 crop composition. Based on the low influence of available water content on crop water consumption found in Tuninetti et al. (2015) and Zhuo et al. (2014), soil parameters are not harmonized. Aqua21 is driven by climate forcing CRU TS3.21 monthly data, downscaled using daily pattern ERA40/ERA interim with method Van Beek et al. (2011) on a 30x30 arc minute resolution (Hogeboom et al., 2020, unpublished). This forcing is used in the PCR-GLOBWB-run as well.

2.2.3. Evaluating model output: comparing irrigation withdrawal and consumption from both models

Research question 1 aims to evaluate the differences in irrigation withdrawal and consumption between Aqua21 and the harmonized PCR-GLOBWB run. Irrigation withdrawal is chosen as a parameter to assess to what extent Aqua21 and PCR-GLOBWB are similar, as it is a parameter which to a large extent determines the total demand for groundwater, and because it is reported per irrigated crop class (non-paddy and paddy) in PCR-GLOBWB. In PCR-GLOBWB, water consumption from irrigation is traced as well. Therefore, water consumption from irrigation is compared to the total blue water consumption from irrigation in Aqua21 as well. This gives insight in the amount of irrigation water, which is used effectively, instead of lost through percolation or runoff.

The total annual irrigation consumption per growing season from Aqua21 for each crop class is aggregated into ‘irrigated paddy’, ‘irrigated non-paddy’ and ‘total’, and multiplied by conveyance efficiency factors from Rohwer et al. (2007) to arrive at withdrawal for irrigation. Afterwards, annual Aqua21 irrigation withdrawal volumes are averaged over 1981-2010 and compared to the average over the same period of annual irrigation withdrawals in PCR-GLOBWB.

2.3. Assessing the spatial distribution of the blue water consumption and footprints of crops

Research questions 2 focusses on assessing the spatial distribution of the contribution of surface water, desalinated water, sustainable groundwater, and non-sustainable groundwater to the blue water footprint of crops, globally on a 5x5 arcmin resolution for a long-term average during 1981-2010. To do so, first the relative contributions of non-sustainable and sustainable groundwater, surface water and desalinated water to the total consumption of all water consuming sectors over an abstraction zone are calculated from output data of PCR-GLOBWB. Then, the ratios of the relative contributions of different water sources to the total consumption in an abstraction zone is applied to crop water consumption. From here on, sectoral water consumption and withdrawal calculated in PCR-GLOBWB are denoted as C_{sector} and Wd_{sector}. Consumption and withdrawal from a source are denoted as C_{source} and Wd_{source}. Without the subscript 'sector' or 'source', C refers to crop water consumption, which is calculated in Aqua21.

In PCR-GLOBWB, return flows from irrigation are added to the groundwater storage, while non-irrigation return flows are added to surface water (De Graaf et al., 2014, Sutanudjaja et al., 2018). Figure 3 shows the way abstracted water is pooled in PCR-GLOBWB to meet demands for irrigation and other sectors. For more information on the abstraction zones, see Appendix A.

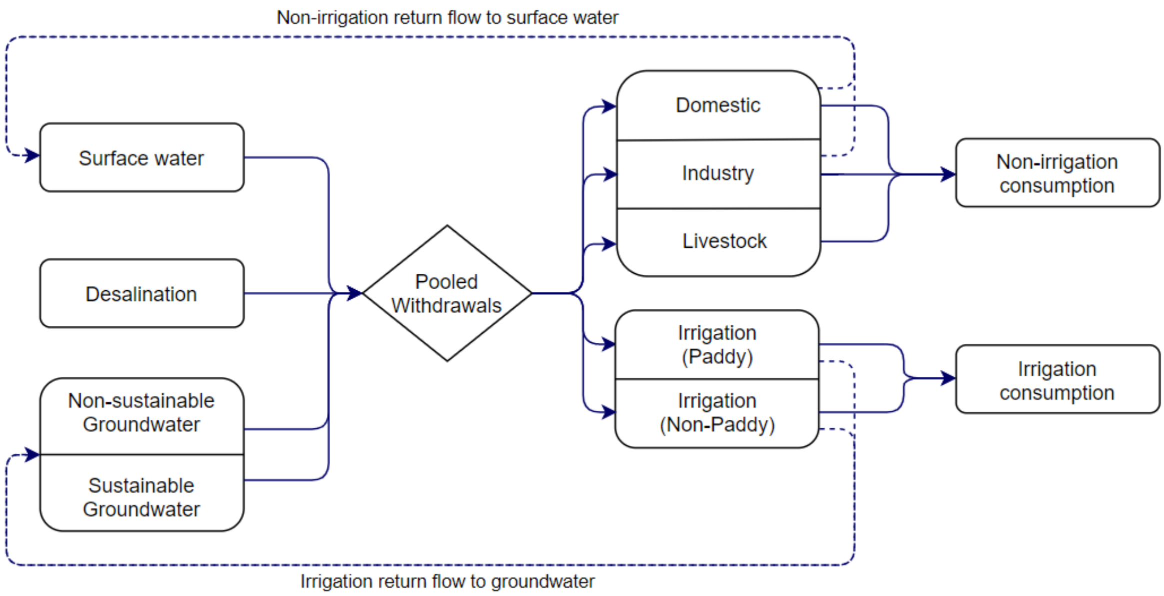


Figure 3 – Visualisation of withdrawal from sources, consumption by sectors and return flows in PCR-GLOBWB in an abstraction zone, adapted from De Graaf et al. (2014). Dotted lines represent return flows.

First, on a grid-cell level, consumption from irrigation is quantified. PCR-GLOBWB does not explicitly calculate consumption from irrigation. For each grid cell, consumption from irrigation could be approximated using PCR-GLOBWB output data by the following equation (Van Beek & Sutanudjaja, November 20, 2020, personal communication):

$$C_{sector,irr} = A_{irr} * ET * \frac{Wd_{sector,irr}}{P+Wd_{sector,irr}} \quad (1)$$

In which:
$C_{sector,irr}$ = sectoral consumption by irrigation (m^3/yr)
A_{irr} = irrigated area (m^2)
ET = crop evapotranspiration (m/yr)
$Wd_{sector,irr}$ = irrigation withdrawal (m/yr)
P = Precipitation (m/yr)

Then, total consumption by all sectors is calculated per abstraction zone by summing all sectoral consumption within abstraction zones:

$$C_{sector,tot} = C_{sector,irr} + C_{sector,dom} + C_{sector,ind} + C_{sector,ls} \quad (2)$$

In which:
$C_{sector,tot}$ = total sectoral consumption (m^3/yr)
$C_{sector,dom}$ = sectoral consumption by the domestic sector (households) (m^3/yr)
$C_{sector,ind}$ = sectoral consumption by the industrial sector (m^3/yr)
$C_{sector,ls}$ = sectoral consumption by livestock (m^3/yr)

After having calculated the total water consumption for all sectors per abstraction zone, the consumption from different sources to meet the total sectoral consumption is quantified per abstraction zone. In PCR-GLOBWB, it is assumed that all desalinated water withdrawal is consumed (see Figure 3, Wada et al., 2014):

$$C_{source,d} = Wd_{source,d} \quad (3)$$

In which:
$C_{source,d}$ = water consumption from desalination (m^3/yr)
$Wd_{source,d}$ = water withdrawal from desalination (m^3/yr)

Surface water consumption per abstraction zone is found by subtracting non-irrigation return flows from surface water withdrawals. When annual return flows occasionally are higher than consumption, consumption is restricted to zero. Return-flows are represented by the symbol RF.

$$C_{source,sw} = \min\left(Wd_{source,sw} - RF_{ind:sw} - RF_{dom:sw}, 0\right) \quad (4)$$

In which:
$C_{source,sw}$ = water consumption from surface water (m^3/yr)
$Wd_{source,sw}$ = water withdrawal from surface water (m^3/yr)
$RF_{ind:sw}$ = return flows from the industrial sector to surface water (m^3/yr)
$RF_{dom:sw}$ = return flows from the domestic sector to surface water (m^3/yr)

Total groundwater per abstraction zone consumption equals groundwater withdrawal minus irrigation return flows, and is restricted to positive or zero values:

$$C_{source,gw,tot} = \min\left(Wd_{source,gw,tot} - RF_{irr:gw}, 0\right) \quad (5)$$

In which:
$C_{source,gw,tot}$ = total consumption from groundwater (m^3/yr)
$Wd_{source,gw,tot}$ = total withdrawal from groundwater (m^3/yr)
$RF_{irr:gw}$ = return flows from irrigation to groundwater(m^3/yr)

It is assumed that the shares of non-sustainable and sustainable groundwater in groundwater consumption are the same as the shares in groundwater withdrawal. Per abstraction zone, non-sustainable groundwater consumption and sustainable groundwater consumption are calculated as:

$$C_{source,gw,nonsust} = \frac{Wd_{source,gw,nonsust}}{W_{source,gw,tot}} * C_{source,gw,tot} \quad (6)$$

$$C_{source,gw,sust} = \frac{Wd_{source,gw,sust}}{Wd_{source,gw,tot}} * C_{source,gw,tot} \quad (7)$$

In which:
$C_{source,gw,nonsust}$ = non-sustainable groundwater consumption (m^3/yr)
$Wd_{source,gw,nonsust}$ = non-sustainable groundwater withdrawal (m^3/yr)
$C_{source,gw,sust}$ = sustainable groundwater consumption (m^3/yr)
$Wd_{source,gw,sust}$ = sustainable groundwater withdrawal (m^3/yr)

Finally, the consumption from different sources over an abstraction zone is divided by total consumption over an abstraction zone to find ratios per source which could be used to find the origin of water consumed in irrigation:

$$C_{source,tot} = C_{source,sw} + C_{source,d} + C_{source,gw,tot} \quad (8)$$
$$R_{sw} = \frac{C_{sw}}{C_{source,total}} \quad (9)$$
$$R_{d} = \frac{C_{d}}{C_{source,total}} \quad (10)$$
$$R_{gw,nonsust} = \frac{C_{gw,nonsust}}{C_{source,total}} \quad (11)$$
$$R_{gw,sust} = \frac{C_{gw,sust}}{C_{source,total}} \quad (12)$$

In which:
$C_{source,tot}$ = total consumption from all sources (m^3/yr)
R_{sw} = ratio of surface water in consumption from irrigation (-)
R_{d} = ratio of desalinated water in consumption from irrigation (-)
$R_{gw,nonsust}$ = ratio of non-sustainable groundwater in consumption from irrigation (-)
$R_{gw,sust}$ = ratio of sustainable groundwater in consumption from irrigation (-)

The ratios per source for an abstraction zones are then applied to the gridded blue water consumption from irrigation in Aqua21 per crop type for each grid cell within the abstraction zones. In the case of sustainable groundwater, crop water consumption from capillary rise is added to the sustainable groundwater via irrigation (see Figure 1):

$$C_{sw} = C_{irr} * R_{sw} \quad (13)$$
$$C_{d} = C_{irr} * R_{d} \quad (14)$$
$$C_{gw,nonsust} = C_{irr} * R_{gw,nonsust} \quad (15)$$
$$C_{gw,sust} = C_{cr} + C_{irr} * R_{gw,sust} \quad (16)$$

In which:
C_{sw} = (crop) water consumption from surface water (m^3/yr)
C_{irr} = (crop) water consumption from irrigation (m^3/yr)
C_{d} = (crop) water consumption from desalination (m^3/yr)
$C_{gw,nonsust}$ = (crop) water consumption from non-sustainable groundwater (m^3/yr)
$C_{gw,sust}$ = (crop) water consumption from sustainable groundwater (m^3/yr)
C_{cr} = (crop) water consumption from capillary rise (m^3/yr)

It should be noted that C_{irr} and C_{cr} per grid cell per crop in Aqua21 are reported per growing season on the harvest date of a growing season. If a crop in Aqua21 grows from October in one year to a harvest date in February in the second year, all water consumption is added to the annual water consumption in the second year. Furthermore, it can occur that no consumption in an abstraction zone is present in PCR-GLOBWB, while Aqua21 does show consumption from irrigation. In that case, the ratios R could not be calculated, thus consumption from irrigation is not attributed to a certain source.

Gridded crop production is found by multiplication of crop yield from Aqua21 in ton/ha and harvested area. For results on a national level, crop production and consumption are summed within a country. for each of the 24 assessed crop types (see Appendix B), surface water, desalinated water, non-sustainable groundwater, and sustainable groundwater consumption [m^3] is divided by the total (both rainfed and irrigated) crop production [ton] per country to find surface water, desalinated water, non-sustainable groundwater and sustainable groundwater footprints [m^3/ton]. Total production, instead of irrigated production, is needed to assess how many cubic meters of non-sustainable groundwater is needed to produce an average ton of a certain crop in a country. For selected crops which either have a large share in global non-sustainable groundwater consumption, or large non-sustainable groundwater footprints, top-producing countries are compared on their contribution of non-sustainable groundwater to the blue water footprint.

Several assumptions are made in the process of allocating the blue water footprint of crops to different sources. It is assumed that within an abstraction zone, the split between non-sustainable groundwater sustainable groundwater, surface water and desalination stays constant disregarding the consuming sector. In reality, it may well be that the agricultural sector relies more on groundwater resources, while industries consume more surface water, or vice versa. In abstraction zones where agriculture is the most dominant or the only water consumer, this assumption causes no problem.

2.4. Evaluating interannual variability and trends

For research question 3, between the years 1981 and 2010, interannual variability and trends in annual non-sustainable groundwater consumption, footprints, and the relative share of non-sustainable groundwater within blue water consumption and footprints of crops are assessed. For the total of all assessed crops, as well as for selected crops which either have a large share in global non-sustainable groundwater consumption, or large non-sustainable groundwater footprints, temporal variability and trends in blue water consumption and footprints are assessed. The variability in water consumption and footprint time series over the years is assessed using the coefficient of variation. Linear interpolation is used to calculate trends in water consumption and footprints over the years. Not every linear trend is statistically significant. According to Sun et al. (2013a), the Mann-Kendall test is recommended by the WMO to evaluate the presence of statistically significant trends in hydrological and climatological time series. The test is applied using the Python package provided by Hussain & Mahmud (2019). Significance is tested with a p-value of 0.05, in line with Wisser et al. (2010).

3. Results

In this chapter, first, the irrigation withdrawal and consumption from irrigation between Aqua21 and PCR-GLOBWB is assessed, followed by a description of the spatial distribution of the different types of the blue water footprint of crops for a long-term average, and per year to assess interannual variability and trends.

3.1. Comparison of irrigation withdrawal and consumption from irrigation between both models

In this section, irrigation withdrawal for the crop types ‘paddy’, ‘non-paddy’ and total, as well as consumption from irrigation are compared between PCR-GLOBWB and Aqua21. Both models are compared at global, national and sub-national level for the most water consuming countries.

3.1.1. Comparison at the global level

The differences in global average irrigated water withdrawal and consumption from irrigation in PCR-GLOBWB and Aqua21 between 1981 and 2010 are large (Table 1). Paddy irrigation withdrawal in PCR-GLOWB nearly doubles Aqua21 paddy withdrawal. Paddy rice makes up roughly 80% of the total irrigation withdrawal in PCR-GLOBWB. For non-paddy crops, the relative difference in non-paddy withdrawal equals 85.1%, showing much larger non-paddy crop withdrawals in Aqua21 than in PCR-GLOBWB. The resulting total withdrawal and the part of it which is consumed by crops is larger in Aqua21 than in PCR-GLOBWB on a global scale.

Table 1 – Global irrigation withdrawal and consumption from irrigation, averaged over 1981-2010.

Crop type	**PCR-GLOBWB (km^3/yr)**	**Aqua21 (km^3/yr)**	**Difference (km^3/yr)**	**Difference, relative to Aqua21 (%)**
Paddy withdrawal	469	229	240	104.5
Non-paddy withdrawal	96	642	-546	-85.1
Total withdrawal	565	871	-306	-35.2
Total consumption from irrigation	294	491	-198	-40.2

According to Van Beek (2 November 2020, personal communication), the relatively large share of paddy rice in total irrigation withdrawal is found in other PCR-GLOBWB-runs as well and is probably due to the way paddy fields are modelled in PCR-GLOBWB. Depending on the soil hydraulic conductivity, irrigation water added to keep the water level constant will percolate into the soil and thus is not consumed. A similar effect of percolation is found in Chapagain and Hoekstra (2011), who found a percolation volume of about 75% of water consumption for global rice production between 2000-2004 using the FAO CROPWAT model and an average blue water consumption for rice of 612 km^3/yr. Taking blue water consumption as the difference between rainfed water consumption and potential water consumption without simulating paddy fields, Mekonnen & Hoekstra (2010) find a global blue water consumption for rice of only 202 km^3/yr, averaged over 1996-2005, which is three times less.

The difference in non-paddy crops could be caused by differences in evapotranspiration in Aqua21 and PCR due to different modelling of crop growths using a crop growth model (Aqua21) and a fixed parameterization (PCR-GLOBWB), although the influence from this is not expected to be large, as both models use the same crop coefficients. Another possibility is that crops have a lower share of blue water in their total water consumption in PCR-GLOBWB than in Aqua21 due to different irrigation water requirements and soil water balance.

3.1.2. Geographical distribution of differences

On a national level, most countries have a smaller paddy and a larger non-paddy withdrawal in Aqua21 than in PCR-GLOBWB, as could be seen in Figure 4 below. The slope in the linear trend for paddy in Figure 4 is 0.46, meaning that for every cubic meter of irrigation water withdrawn in Aqua21, about two cubic meters are withdrawn for irrigation in PCR-GLOBWB. With a coefficient of determination of 0.99, this pattern is visible all over the world. Top-consumers India and China fit well in this trend. For non-paddy crops, countries with large withdrawals withdraw about five to eight time more water from irrigation in Aqua21 than in PCR-GLOBWB. For smaller countries, this is even more. Countries which withdraw less water for irrigation for non-paddy crops show even larger differences than top-withdrawing countries. Ultimately, differences in total irrigation withdrawal level out a bit, depending on the share of water withdrawal for non-paddy or paddy crops within a country. Especially in Europe, and even for countries containing paddy area, such as Italy and Spain, differences tend to be large.

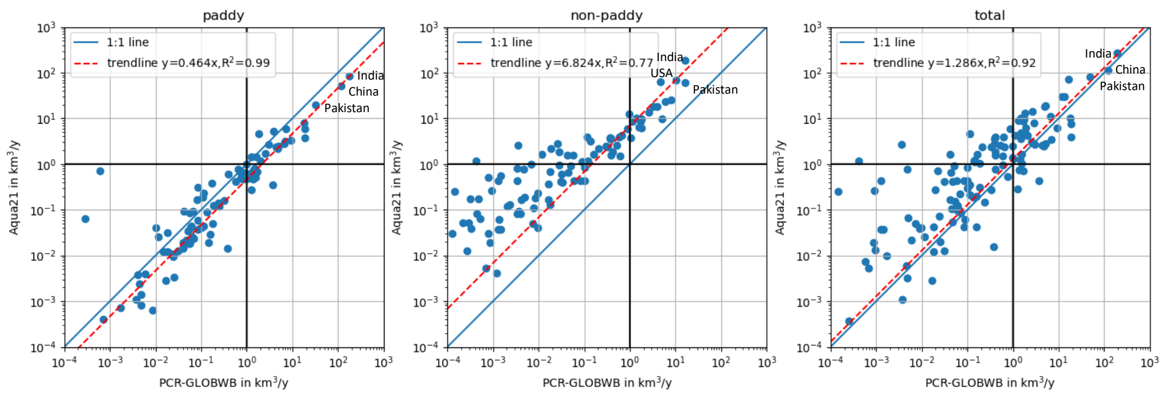


Figure 4 - Comparison of average irrigation withdrawal over 1981-2010 in both models for (a) paddy, (b) non-paddy and (c) total crop types. Each dot represents a country.

Total consumption from irrigation shows a similar fit as total irrigation withdrawal, with a coefficient of determination of 0.93 (Figure 5). Top consuming countries fit better in the trend than many less water consuming countries, just as for non-paddy in Figure 4. Countries without, or with a small share of rice in their total crop production show less agreement in total water consumption than countries with a large share of rice in their national crop production.

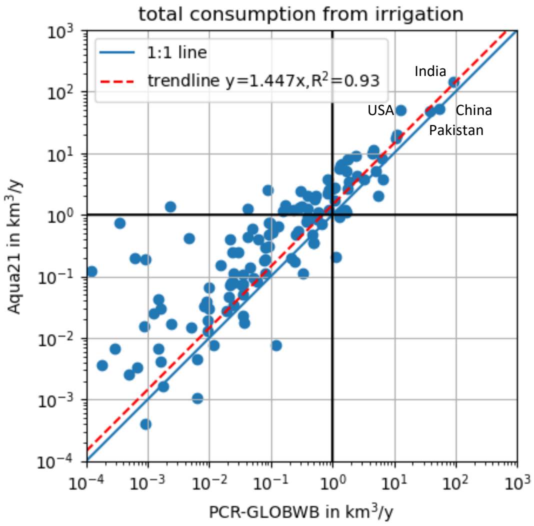


Figure 5 - Comparison of average consumption from irrigation over 1981-2010 in both models for the total of all crop types. Each dot represents a country.

In most areas globally, the difference between PCR-GLOBWB and Aqua21 consumption from irrigation, relative to Aqua21 consumption from irrigation is lower than -50% (Figure 6). Within the USA and Mexico, a few locations, for example in the Mississippi embayment exist where PCR-GLOBWB shows more consumption from irrigation than Aqua21. Within the Middle East, Iraq has locations in which PCR-GLOBWB has a larger consumption from irrigation as well. Areas in which PCR-GLOBWB consumption from irrigation is larger than Aqua21 consumption from irrigation often coincides with semi-arid areas near rivers or in deltas. In Aqua21, due to the high groundwater tables, capillary rise is used to fulfil a large part of the blue water consumption, so that less irrigation water is needed.

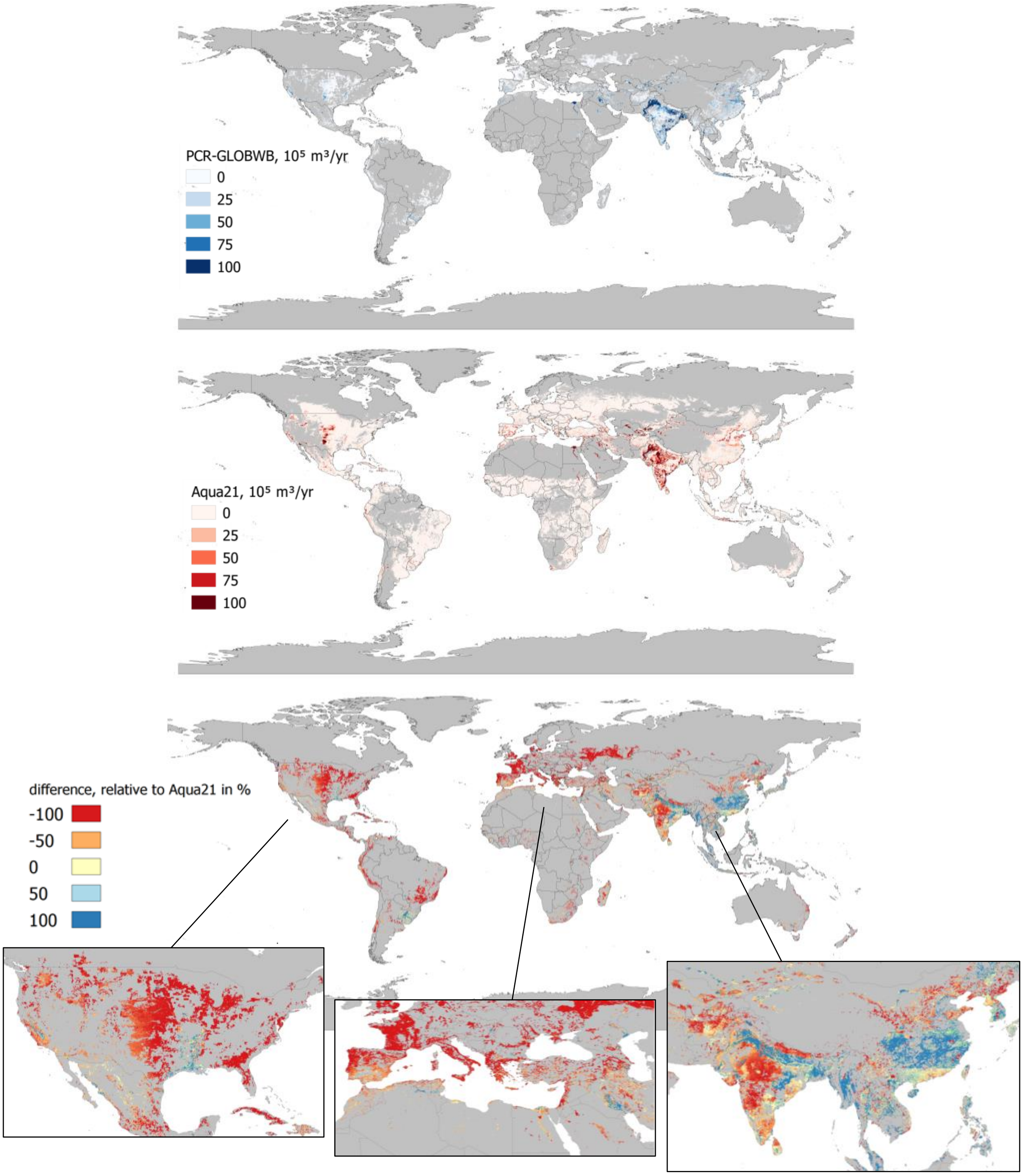


Figure 6 – Global maps of grid based consumption from irrigation in Aqua21 and PCR-GLOBWB, averaged over 1981-2010. Top: Consumption from irrigation in PCR-GLOBWB. Centre: Consumption from irrigation in Aqua21. Bottom + insets: Difference between 1981-2010 grid-based average PCR-GLOBWB and Aqua21 consumption from irrigation, relative to Aqua21 consumption from irrigation. Negative (red) values mean a larger consumption from irrigation in Aqua21 than in PCR-GLOBWB. Positive (blue) values mean a larger consumption from irrigation in PCR-GLOBWB than in Aqua21.

Within countries, differences in withdrawal and consumption of irrigation water can be substantial, see Figures 7 and 8, respectively. For paddy rice, countries with a large spatial variation in difference in withdrawal between PCR-GLOBWB and Aqua21 are Indonesia, Thailand, and Bangladesh. For non-paddy crops, Pakistan and Egypt especially show a relatively large spatial variation. For the total of all crops, the spatial variation is large for India, China, and Pakistan, mainly due to their large share of paddy rice fields in which PCR-GLOBWB withdraws more water than Aqua21, the spatial variation is large for India, China and Pakistan. India and China are the only countries within the top-10 total irrigation water withdrawing countries with grid-cells in their third quartile (between the 50th and 75th percentile) with larger total irrigation withdrawals in PCR-GLOBWB than in Aqua21 (Figure 7). For consumption from irrigation (Figure 8), roughly the same pattern emerges as from total irrigation withdrawal. India, China and Pakistan, three major rice producing countries, are the only countries for which grid cells within the 75th percentile show higher consumption in PCR-GLOBWB than in Aqua21.

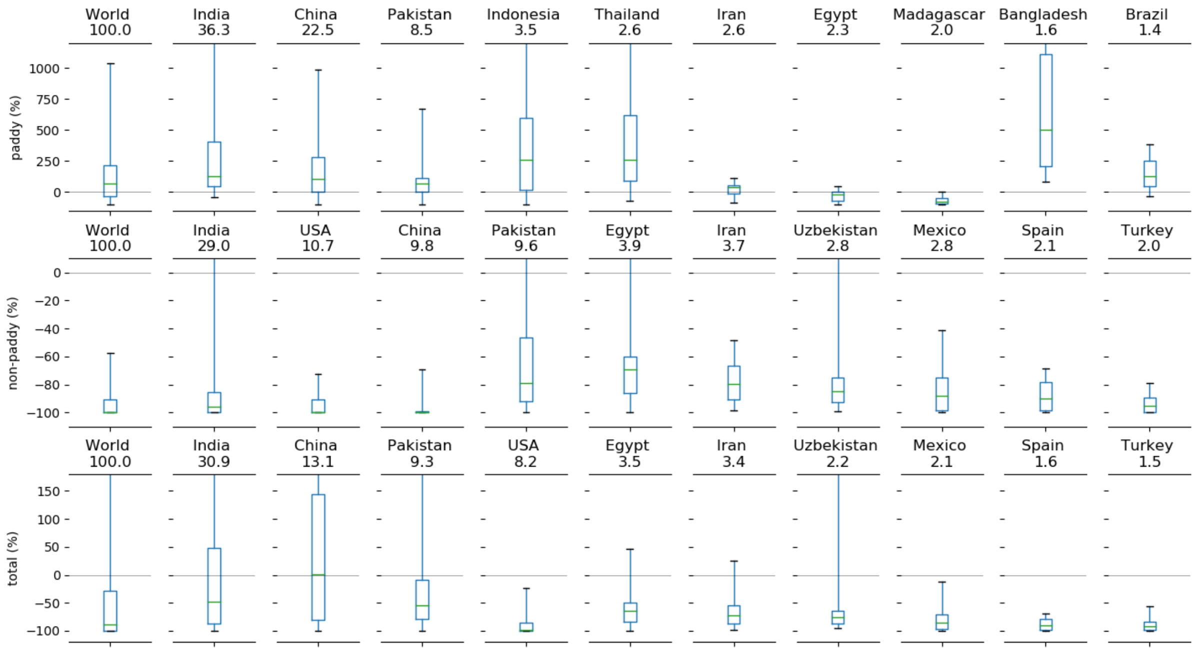


Figure 7 – Spatial distribution of difference between gridded PCR-GLOBWB and Aqua21 1981-2010 average withdrawal for irrigation, relative to Aqua21 irrigation withdrawal for the world and the ten countries with the highest irrigation withdrawal in Aqua21 for total, paddy, and non-paddy. Values underneath the country name represent the percentage of the worldwide Aqua21 irrigation water withdrawal per crop type for each country. Boxes show 25th, 50th and 75th percentile intervals. Whiskers range from the 5th to 95th percentile interval. Tops of whiskers may be cut of from the plots for better overall visibility.

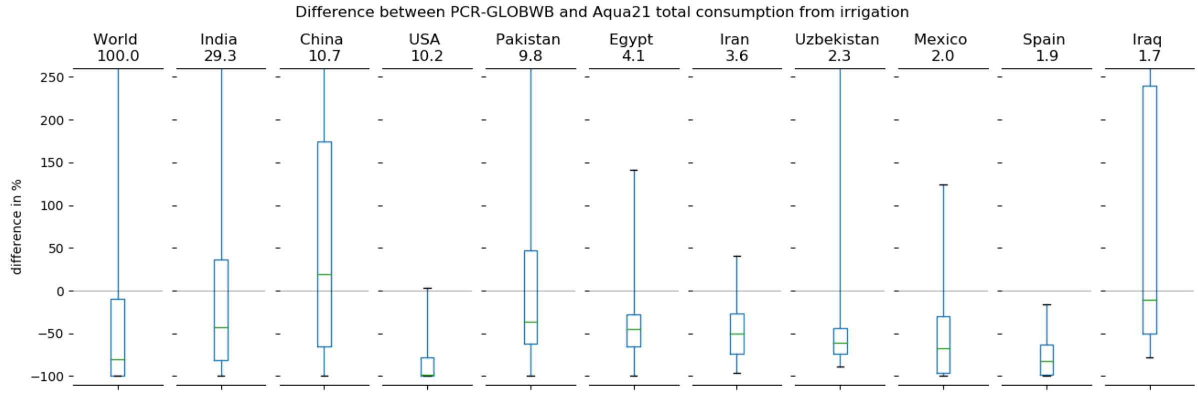


Figure 8 – Spatial distribution of difference between gridded PCR-GLOBWB and Aqua21 1981-2010 average total consumption from irrigation, relative to Aqua21 total consumption from irrigation for the world and the ten countries with the highest total water consumption from irrigation in Aqua21. Values underneath the country name represent the percentage of the worldwide Aqua21 total consumption from irrigation for each country. Boxes show 25th, 50th and 75th percentile intervals. Whiskers range from the 5th to 95th percentile interval. Tops of whiskers may be cut of from the plots for better overall visibility.

3.1.3. Implications for the calculation of non-sustainable groundwater consumption

On global to local level, differences in Aqua21 and PCR-GLOBWB consumption from irrigation exist, and may become substantial, for both non-paddy as paddy irrigation. Furthermore, even within countries, a wide spatial distribution in differences may be present. In applying ratios of non-sustainable groundwater, sustainable groundwater, desalination, and surface water in total water consumption in PCR-GLOBWB to consumption from irrigation in Aqua21, one must keep in mind the location and spatial distribution of deviations in consumption from irrigation in both models.

Large differences between global hydrological models are not uncommon. Still, it is striking that PCR-GLOBWB show far less irrigation withdrawal and consumption from irrigation for so many regions in the world, with important groundwater consuming regions as the USA and large regions in India among them, which may indicate an underestimation of consumption from irrigation and irrigation withdrawal in PCR-GLOBWB. Although both models agree on hotspot areas with large irrigation withdrawals and consumption, low irrigation water withdrawals in PCR-GLOBWB will lead to less non-sustainable groundwater consumption, as groundwater abstractions will more often remain smaller than groundwater recharge, and hence, the proportion of non-sustainable groundwater will be lower. For areas using groundwater in arid regions for aquifers for which recharge is negligible, such as the Nubian sandstone aquifer system underlying North Africa and the Arabian aquifer system (Margat & van der Gun, 2013), the non-sustainable groundwater consumption will probably still show a large share of non-sustainable groundwater in the total blue water footprint, as sustainable groundwater and surface water are (almost) absent. However, irrigation in semi-arid regions where recharge to aquifers is larger, especially in the USA, where the difference between Aqua21 and PCR-GLOBWB irrigation withdrawal is large, the low PCR-GLOBWB irrigation withdrawal can cause larger underestimation of the share of non-sustainable groundwater consumption.

3.2. Spatial analysis of the long-term average blue water footprint of crops

In this chapter, the spatial distribution of the contributions of surface water, desalinated water, sustainable and non-sustainable groundwater to the blue water consumption and blue water footprint of different crop types is assessed, averaged over the years 1981-2010. Emphasis is placed on the quantification of non-sustainable groundwater consumption by crops. First, the composition of the global water consumption of different types of blue water is shown for the sum of all crop types. Then, the geographical distribution of different types of blue water consumption is shown, followed by the global total consumption of different types of blue water per crops, globally and for the most important groundwater consuming nations. Finally, non-sustainable groundwater footprints and total blue water footprints are compared for different crops in different countries.

3.2.1. Composition of the global blue water consumption

Globally, averaged over 1981-2010, the total blue water consumption for all crops assessed is 816 km^3/yr, of which 327 km^3/yr is surface water, 4 km^3/yr is desalinated water and 483 km^3/yr comes from groundwater. Non-sustainable groundwater consumption accounts for 47 km^3/yr, which equals 6% of the total blue water consumption. 324 km^3/yr of the groundwater enters the root zone of crops via capillary rise, which is roughly 40% of the total blue water consumption (Figure 9). Sustainable groundwater consumption, which is the sum of capillary rise consumption and sustainably pumped groundwater for irrigation accounts for 436 km^3/yr. About 1 km^3 which is 0.2% of the blue water consumption calculated in Aqua21 takes place in abstraction zones for which PCR-GLOBWB does not report any water consumption for irrigation. This portion of the irrigation water thus could not be attributed to any water source. About one third of the water used to irrigate crops comes from groundwater (Figure 9). Non-sustainable groundwater consumption accounts for roughly 9% of total irrigation water consumption. What is striking, is the large consumption of capillary rise, given that none of the literature reviewed in the state of the art (Section 1.2) explicitly demonstrates the large importance of capillary rise in the blue water footprint of crops.

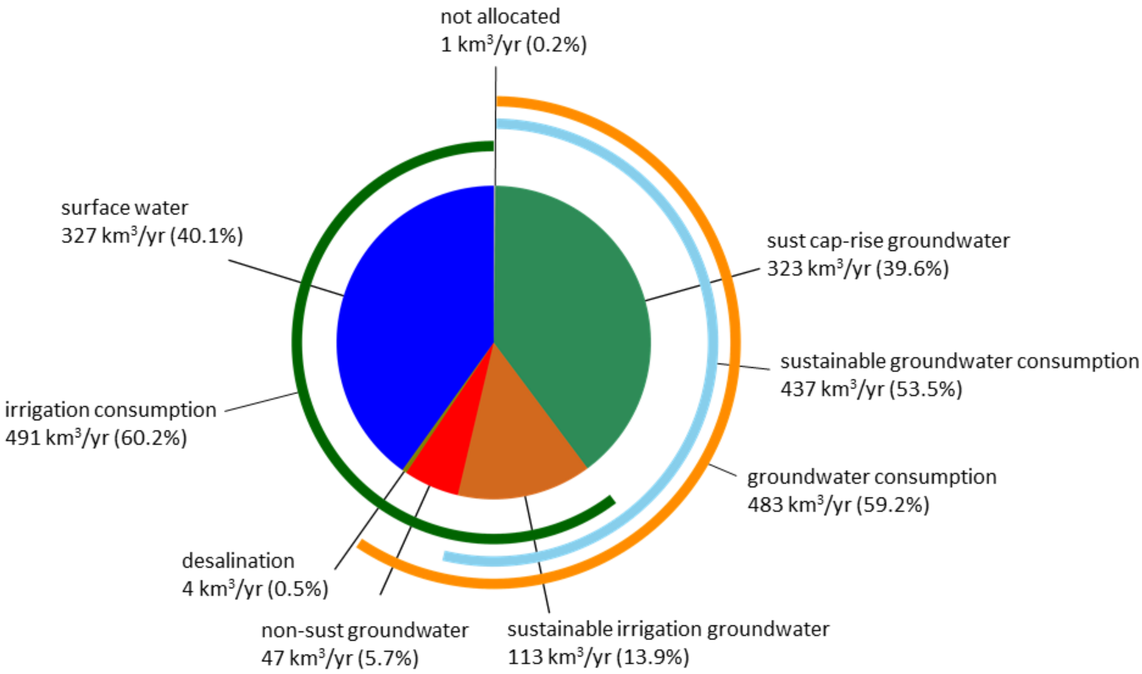


Figure 9 - Global distribution of sources of blue water consumption for total crop production. Fractional contributions of each water source are shown in the inner circle. Arcs outside the circle represent aggregations on irrigation consumption (dark green), sustainable groundwater consumption (light blue) and groundwater consumption (orange). Cap-rise = capillary rise, sust = sustainable.

3.2.2. Geographical distribution of different types of blue water consumption

Figure 10 includes global maps on total blue water, surface water, sustainable (including capillary rise) and non-sustainable groundwater consumption for irrigation. Because desalination plays a minor role in water consumption by irrigation, this source is not included in Figure 10. Almost all areas with large blue water consumption and non-sustainable groundwater consumption are located in arid and semi-arid areas. Sustainable groundwater consumption also occurs in areas where surface water is present, but hard to control, such as Bangladesh (Margat & Van der Gun, 2013). Hotspot areas with large non-sustainable groundwater consumption quantities can be found in semi-arid regions coinciding with aquifers with large groundwater footprints in Gleeson et al. (2012), such as the Western Mexico, High Plains, North Arabian, Persian, Upper Ganges, and North China plain aquifers. Apart from the regions with high groundwater footprints in Gleeson et al. (2012), high non-sustainable groundwater consumption volumes can be witnessed in Spain, described in Aldaya et al. (2008) and Dumont et al. (2013), and Italy, discussed in Aldaya & Hoekstra (2010). Furthermore, all hot-spots found here have large non-sustainable blue water consumption according to Mekonnen & Hoekstra (2020) as well.

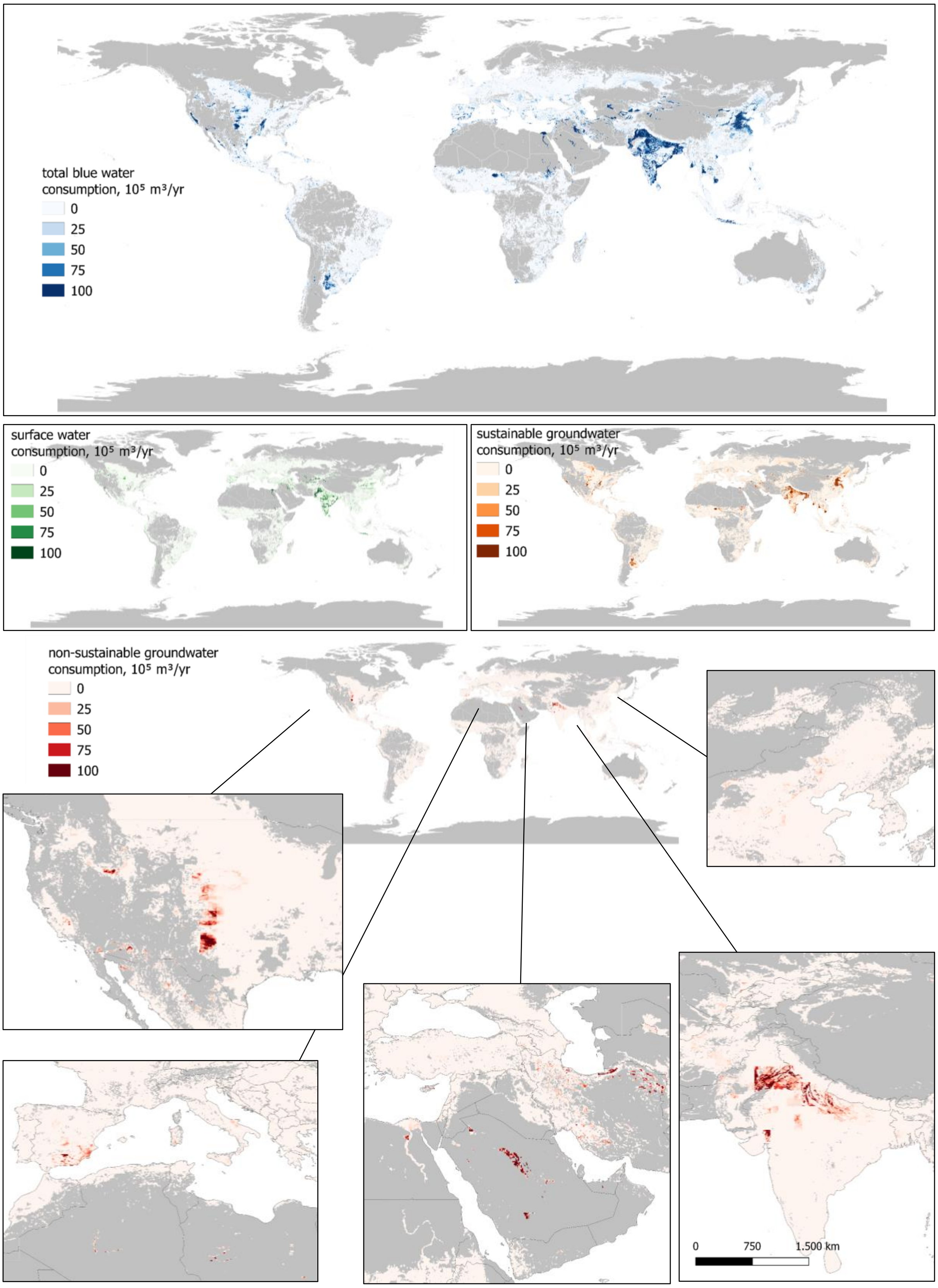


Figure 10 – Global maps of consumption per grid cell for total of all crop types. Top: Total blue water consumption. Central left: Surface water consumption. Central right: sustainable groundwater consumption. Bottom + insets: Non-sustainable groundwater consumption. All insets have the same scale.

3.2.3. Global blue water consumption and footprints for crop types

Crops with the largest blue water consumption and non-sustainable groundwater consumption include wheat, rice, maize and cotton (Figure 11). With 16 km^3/yr, wheat is the largest non-sustainable groundwater consumer, accounting for 35% of the global non-sustainable groundwater consumption for crops, followed by rice (7 km^3/yr, 15%) and cotton (6 km^3/yr, 14%), maize (5 km^3) and sugar cane (2 km^3). Dalin et al. (2017) find the same top-five groundwater depleting crops, but in another order. Not surprisingly, the crops with the largest blue water footprint also account for the largest non-sustainable groundwater consumption, due to fact that they are grown all over the globe, thus also in areas where non-sustainable groundwater is withdrawn for irrigation.

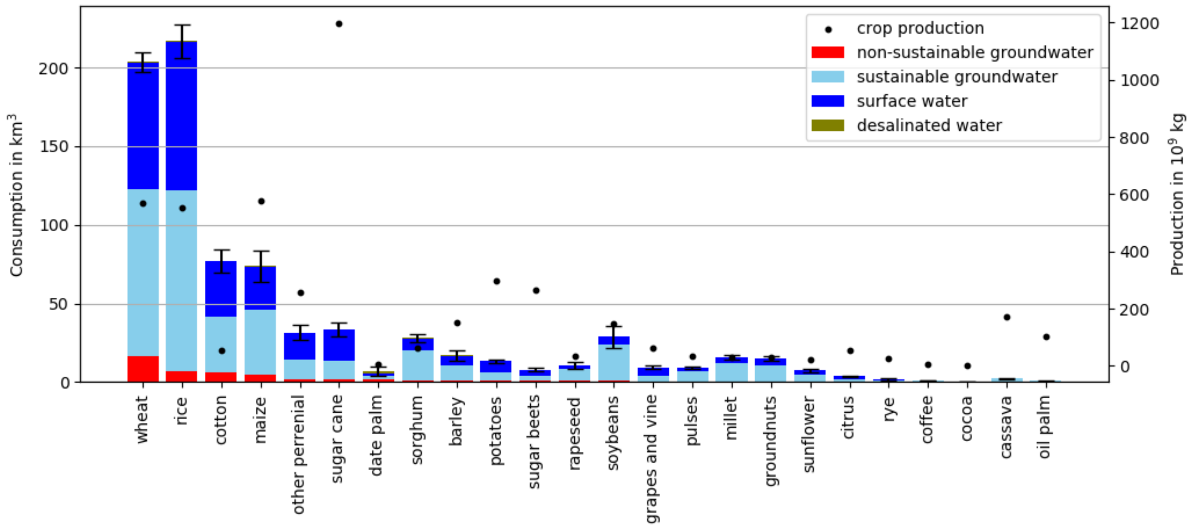


Figure 11 - Global blue water consumption per crop type, averaged over 1981-2010, ordered from left to right by non-sustainable groundwater consumption. Bars represent the different types of the blue water consumption (left axis), dots represent crop production (right axis). Whiskers represent standard deviations of total blue water consumption over time.

Date palm and cotton have the largest non-sustainable groundwater footprints, with 331 m^3/ton and 117 m^3/ton respectively, followed by wheat (29 m^3/ton), rapeseed (23 m^3/ton), and sorghum (20 m^3/ton) (Figure 12). In arid areas where date palm is produced, aquifers are the only reliable water supply apart from desalination. Cotton is known for its large blue water footprint. About half of all cotton fields are irrigated, and cotton is mainly grown in Mediterranean and other warm climatic regions (Chapagain et al., 2006; Mekonnen & Hoekstra, 2011). The crops with the largest relative contribution of non-sustainable groundwater to their blue water footprint are date palm (22%), sugar beets (10%), cotton (8%) and wheat (7%). Maize, which is one of the crops with the largest global non-sustainable groundwater and total blue water consumption, has a relatively low non-sustainable groundwater footprint and total blue water footprint, as it is a relatively water-efficient crop to grow with a water footprint almost twice as low as Wheat according to Mekonnen & Hoekstra (2011). Non-sustainable groundwater plays no role at all in the production of cocoa, oil palm and cassava. These crops have in common that they are mainly grown in tropical regions, where precipitation is abundant, so that blue water and non-sustainable groundwater specifically is not needed. Furthermore, Margat & Van der Gun (2013) state that in large regions in South America and Africa, where these crops are grown, groundwater irrigation systems are not present because of lacking financial resources and needed technical knowhow. Although rice accounts for a large absolute non-sustainable groundwater consumption, only 3% of the blue water consumption for rice production globally comes from non-sustainable groundwater. The role of desalination in crop production is marginal. It only plays a significant role in the production of date palm, which is mainly produced in Arabic and north-African countries.

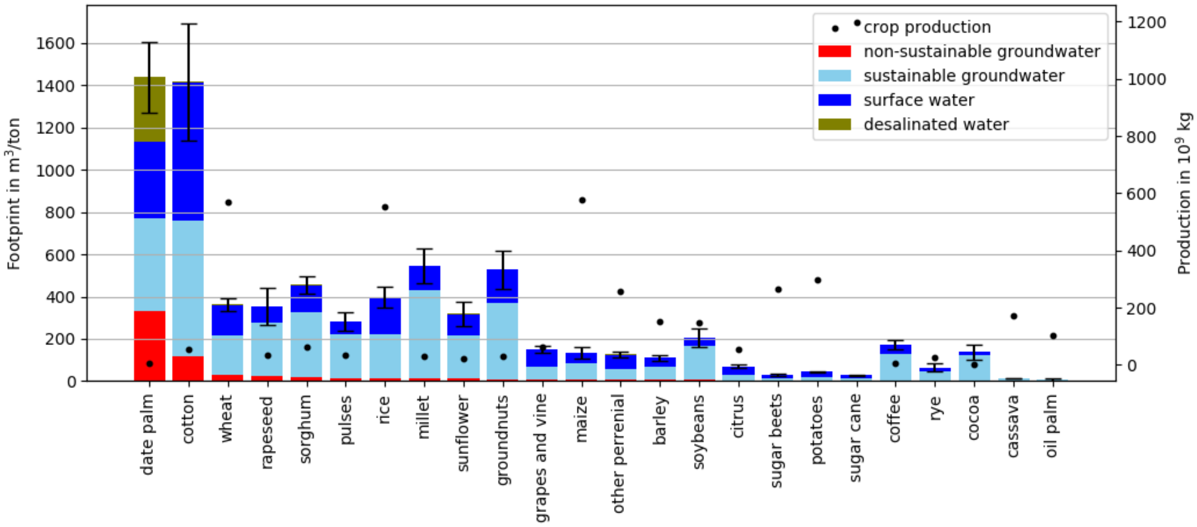


Figure 12 – Global blue water footprints per crop type, averaged over 1981-2010, ordered from left to right by non-sustainable groundwater consumption. Bars represent the different types of the blue water footprint (left axis), dots represent crop production (right axis). Whiskers represent standard deviations of total blue water footprints over time.

Rice, maize and cotton have the largest standard deviations over time for their total blue water consumption. The crops with the largest standard deviations, relative to the mean (coefficient of variation) are rye and date palm, indicating a large interannual variability. Cotton and date palm have the largest standard deviation over time for the blue water footprint. The largest interannual variability is present for oil palm and cocoa, two crops with negligible non-sustainable groundwater footprints.

3.2.4. The share of non-sustainable groundwater consumption of crops across nations

The largest non-sustainable groundwater consumption is found in India (13 km^3/yr) and the USA (11 km^3/yr). Pakistan, Saudi Arabia, and Iran follow with 8, 6 and 4 km^3/yr respectively (Figure 13). Countries with a relatively large total blue water consumption for crops, such as China, does not necessarily have a large non-sustainable groundwater consumption. On the other side of the spectrum, countries in the Middle East and North Africa (MENA) do not have a large total blue water consumption, but the fraction of it which comes from non-sustainable groundwater is relatively large. Countries with the largest share of non-sustainable groundwater in total blue water consumption for crop production are Bahrain (82%), Saudi Arabia (71%) and Libya (24%). Island states without access to large fresh surface water bodies, such as Cyprus and Malta are listed in the top-10 countries with the largest non-sustainable groundwater fractions as well, with 15% and 11% of total blue water consumption for crop production respectively (see Figure 13). Other regions with large non-sustainable groundwater fractions coincide with hotspot-areas described in section 3.2.2 with large absolute non-sustainable groundwater consumption for crops, such as the High Plain Aquifer, Upper Ganges Aquifer, the North China Plain, Spain and Italy.

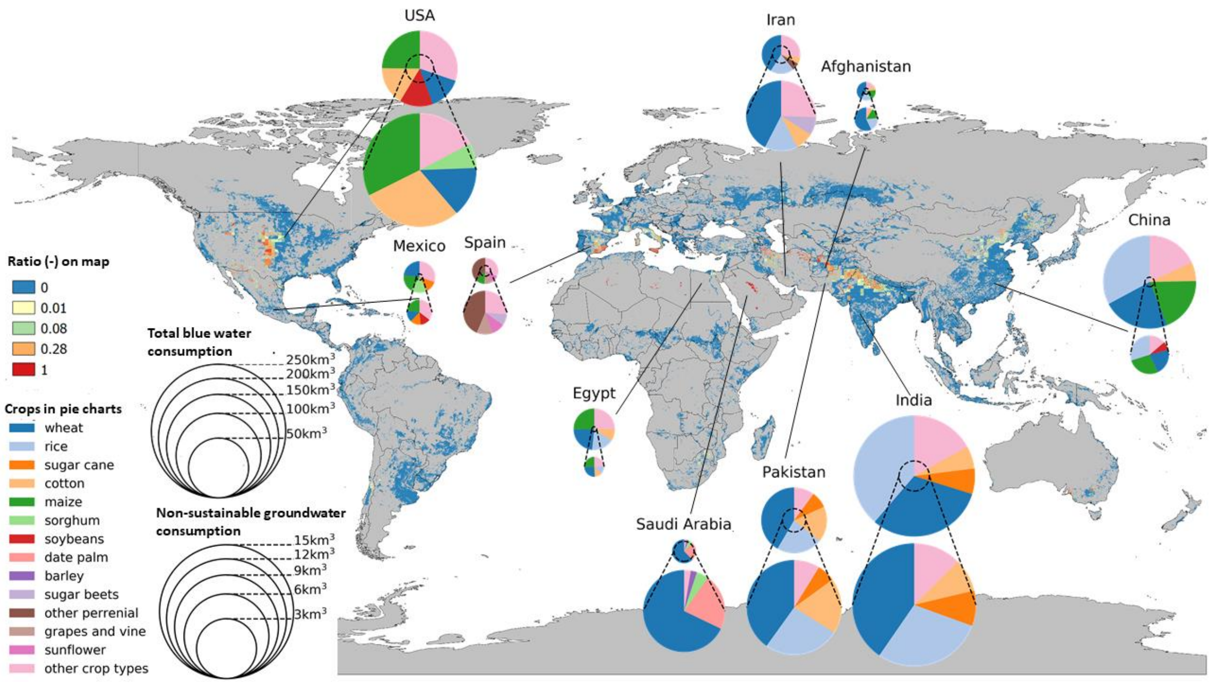


Figure 13 – Global map of ratio of non-sustainable groundwater consumption to total blue water consumption in grid cells. For top 10 non-sustainable groundwater consuming countries, pie charts show the share of the four most consuming crops for total blue water consumption (upper pie chart) and non-sustainable groundwater consumption (lower pie chart). The dotted circle in the upper pie chart represents the total non-sustainable groundwater consumption for a country on the same scale as total blue water consumption.

In almost every top 10 non-sustainable groundwater consuming country, the globally most non-sustainable groundwater consuming crops such as wheat, cotton, and sugar cane play an important role. In Asian countries, rice is an important non-sustainable groundwater consumer as well. Crops with large blue water consumption do not necessarily consume a large amount of non-sustainable groundwater as well and vice versa. Soybeans for example account for 14% of the total blue water consumption for crop production in the USA, but only for 4% of the non-sustainable groundwater consumption for crop production in the USA.

For the non-sustainable groundwater hotspot in the USA, Esnault et al. (2014) state that most groundwater stress in the Central Valley and High Plains aquifers is induced by crops meant for cattle feed. From these crops assessed by Esnault et al. (2014), hay and haylage are not included in this study. However, maize, which according to Esnault et al. (2014) is grown above the high plains aquifer mainly to feed cattle, accounts for about one-third of the entire US non-sustainable groundwater consumption by crops (Figure 13). Marston et al. (2015) show that crops grown over the USA aquifers are often exported as well, and that Japan for example relies for 9.2% of its domestic cereal supply on cereals produced by overexploited aquifers in the USA. Another example of cross-border effects is shown by Chapagain et al. (2006) for cotton. Chapagain et al. (2006) showed for example that consumption from the European Union has a large influence on blue water resources in India, Uzbekistan, and Pakistan. Figure 13 shows that cotton is one of the main crops consuming non-sustainable groundwater in India and Pakistan. For Uzbekistan, cotton accounts for 65% of total non-sustainable groundwater consumption. According to Dalin et al. (2017), USA, Mexico, Iran, and China are particularly exposed to global food and water risks, due to their large exports and imports from crops grown with non-sustainable groundwater.

3.2.5. Comparison of blue water footprints of crops between nations

From a consumer or policy-maker perspective, it is useful to know per crop which country has a large non-sustainable groundwater footprint, and which country as a small non-sustainable groundwater footprint. In this section, for a selection of most-produced crops (sugar cane, maize, wheat, and rice) and two crops with the largest global average groundwater footprints: cotton and date palm, top producing nations are compared on their blue water footprints.

India, Iran and Pakistan have large blue total, as well as non-sustainable groundwater footprints across multiple crops assessed here, compared to other countries. Within crop types, large differences in blue water footprints exist. Brazil for example, accounts for a large portion of the global production of sugar cane, maize and cotton, without putting pressure on groundwater resources. Date palm, a popular crop in the Middle East and North Africa, is grown with very different blue water footprints per country. Egypt, Iraq and Pakistan have relatively low blue water footprints for date palm without a significant non-sustainable groundwater footprint, whereas the gulf states in general use a large amount of (non-sustainable) groundwater, or energy-consuming desalinated water per ton produced date palm. For maize, it is striking that Egyptian maize production heavily relies on blue water with a blue water footprint of 1203 m^3/ton, compared to a global average of 133 m^3/ton (Figure 14). Most of the Egyptian maize production takes place in the nile delta, and is largely fed with capillary rise, due to high modelled water tables.

From Figure 14, it becomes clear which large differences exist between total blue and non-sustainable groundwater footprints for crops between countries. Knowing that the EU has a large dependence on Indian blue water resources for cotton for example (Chapagain et al., 2006), the results shown here can be helpful in this regard to guide decisions on importing cotton from China or Brazil instead of India or Pakistan for example.

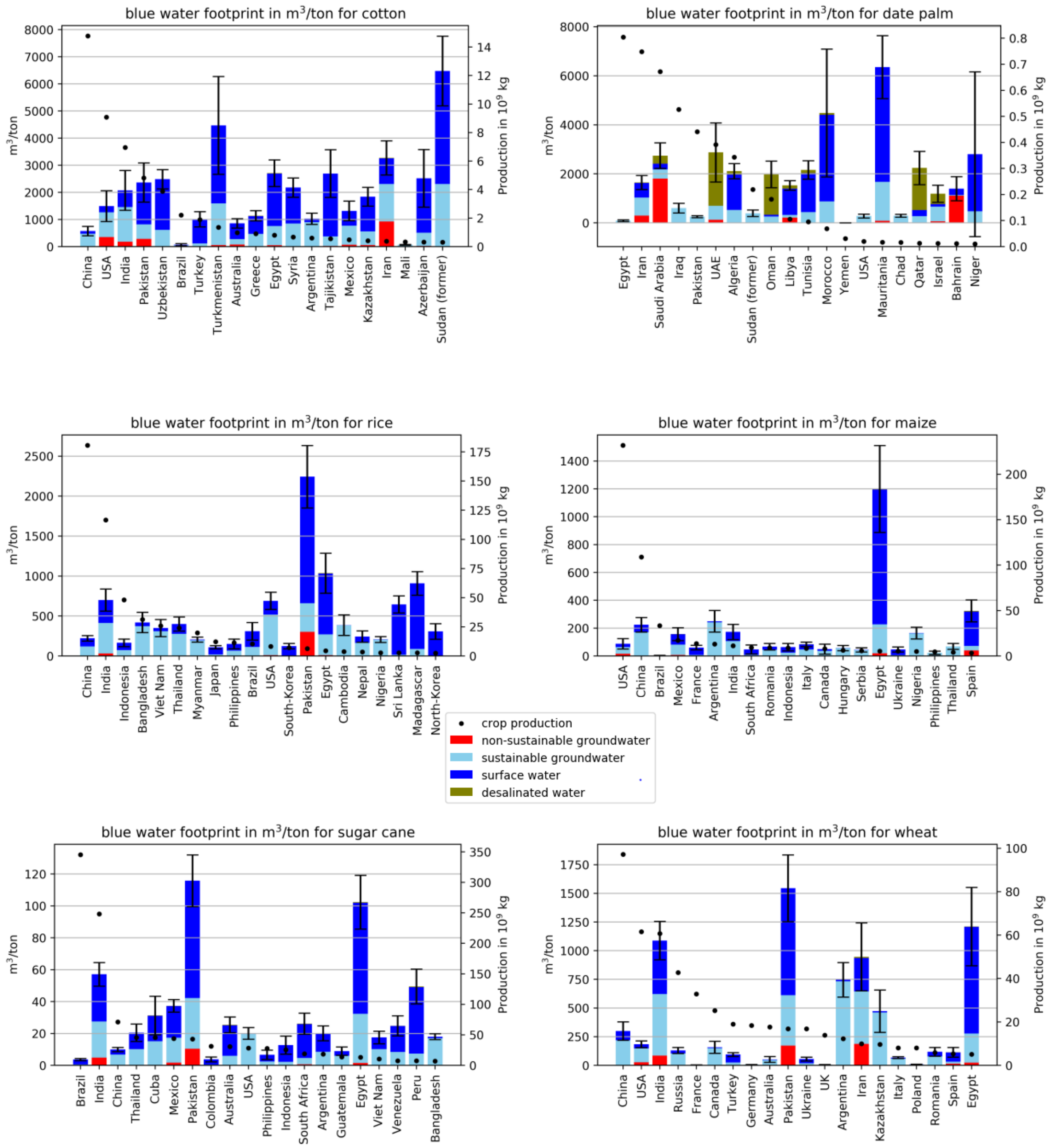


Figure 14 – Blue water footprints for selected crop types, average over 1981-2010. Bars represent the different types of the blue water footprint (left axis), dots represent crop production (right axis). Countries are arranged from left to right by total crop production. Whiskers represent standard deviations of total blue water footprints over time.

3.3. Temporal development in global blue water consumption and blue water footprints of crops

In this section, the long-term trends and interannual variability in the relative and absolute contribution of non-sustainable groundwater to the blue water consumption and footprint of crops is assessed. First, the global temporal development in the different types of blue water consumption between 1981 and 2010 for the total of all crops and different crop types is discussed. Then, the development in blue water footprints of selected crop types and important drivers behind temporal variability are assessed.

3.3.1. Global temporal development in the types of blue water consumption

Over the three decades between 1981 and 2010, total blue water consumption for irrigation for the crops assessed in this research increased from about 780 km^3 in 1981 to about 820 km^3 in 2010 (Figure 15). This increase was significant on the p=0.05 significance level using the Mann-Kendall test. Surface water consumption did not show a significant upward or downward trend on the p=0.05 significance level using the Mann-Kendall test. Sustainable groundwater (including capillary rise) grew slightly. Although the contribution of non-sustainable groundwater is relatively small, non-sustainable groundwater consumption showed, apart from desalination, the largest relative increase and grew from 31km^3 in 1981 to 52km^3 in 2010, which resulted in an increase in the relative share of non-sustainable groundwater in total blue water consumption from about 3% in the beginning of the 1980s to 7% in the 2000s. Several peak events are present in the dataset. In 1992, sustainable groundwater consumption showed a peak due to an outlier in irrigated area in the United States. Non-sustainable groundwater

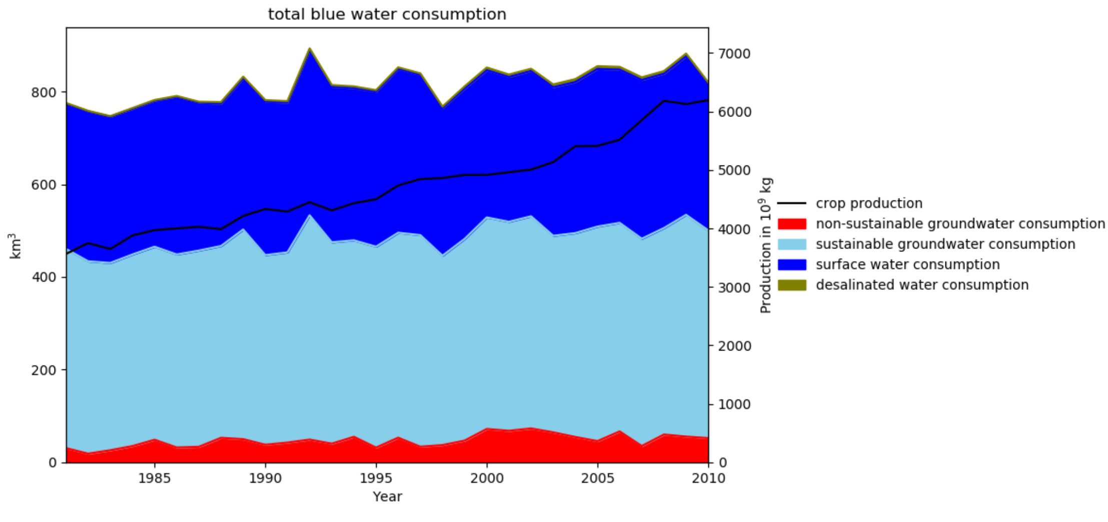


Figure 15 – Global total blue water consumption for crop production for different sources over time (left y-axis), shown together with global crop production (right y-axis).

The increase in non-sustainable groundwater consumption of 1.0 km^3/yr is mainly driven by an increase in wheat and rice (Figure 16), which showed upward trends of 0.30 km^3/yr and +0.18 km^3/yr, respectively. From the selected crop types, maize and cotton have a large coefficient of variation, which in the case of maize represents a large interannual variability. Of all crops, wheat, barley, and rice have the lowest coefficients of variations for non-sustainable groundwater consumption. It should be noted that crops which are produced at smaller scales, such as cocoa and coffee, have higher coefficients of variation than widely produced staple crops, such as wheat and rice.

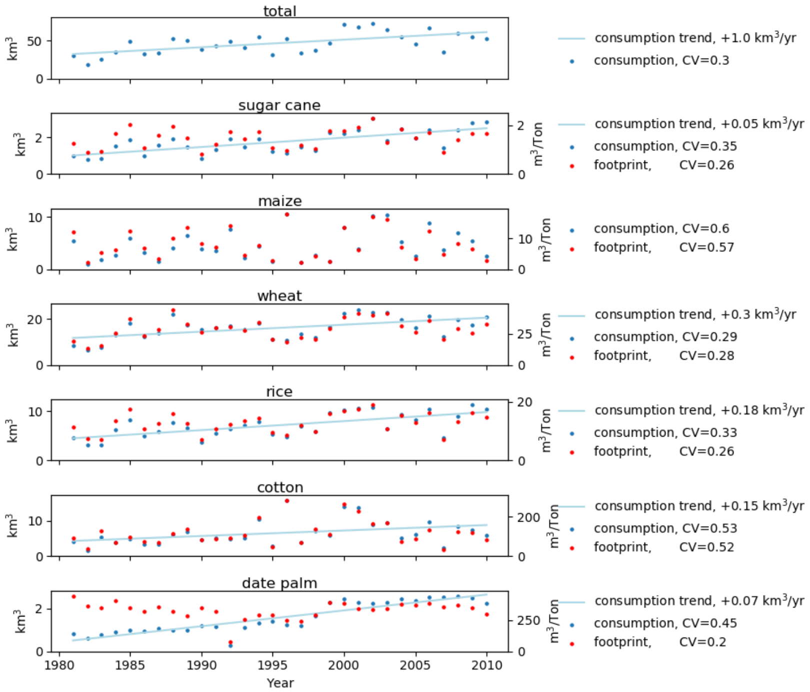


Figure 16 - Non-sustainable groundwater consumption and non-sustainable groundwater footprint for total of all crops and six selected crop types. CV is coefficient of variation (standard deviation divided by mean). Linear trends are shown when trend is tested significant at the P=0.05 significance level with a Mann-Kendall test.

The long-term trend in non-sustainable groundwater consumption is mainly explained by changes in irrigated area, which increased gradually for almost all crops. Interannual differences are mostly the result of differences in evapotranspiration of non-sustainable groundwater. Total evapotranspiration of non-sustainable groundwater (m^3/ha) did not show large upward or downward trends. When an upward trend is seen for evapotranspiration of non-sustainable groundwater, as for sugar cane, this is less large than changes in irrigated area.

3.3.2. Global temporal development in blue water footprints

Here, for the six selected crop types (cotton, date palm, rice, wheat, maize and sugar cane), the global temporal development in water footprints is assessed. Except for date palm, all assessed crop types in Figure 17 show a decreasing trend in total blue water footprints. Because crop production has become more blue water efficient over time, the growing global crop production has not led to a sharp increase in total blue water consumption (Figure 15).

In general, non-sustainable groundwater footprints follow the pattern in interannual variability of total blue water footprints, but do not show large increases or decreases for the long term, causing a slight increase in relative share of non-sustainable groundwater in the blue water footprint of crops. For example, the non-sustainable groundwater footprint for wheat shows an increase (although not significant on the p=0.05 significance level), in contrary to the decreasing trend in total blue water footprint for wheat. This is mainly due to decreasing blue water consumption in north-east China in areas where non-sustainable groundwater does not represent a large share of the total blue water consumption of crops. For maize, a large peak in total blue water footprint in 1992 is not represented in the non-sustainable water footprint. In that year, the USA maize irrigated area is about twice as high as the years before and after. Non-sustainable groundwater consumption for maize increased as well that year, but for many areas in the USA, enough sustainable groundwater was available to accommodate a large part of the extra crop water consumption. These two cases for maize and wheat show that changes in the relative share of non-sustainable groundwater in the blue water footprint of crops for nations is often the consequence of increase or decrease in blue water consumption outside of areas where non-sustainable groundwater is pumped.

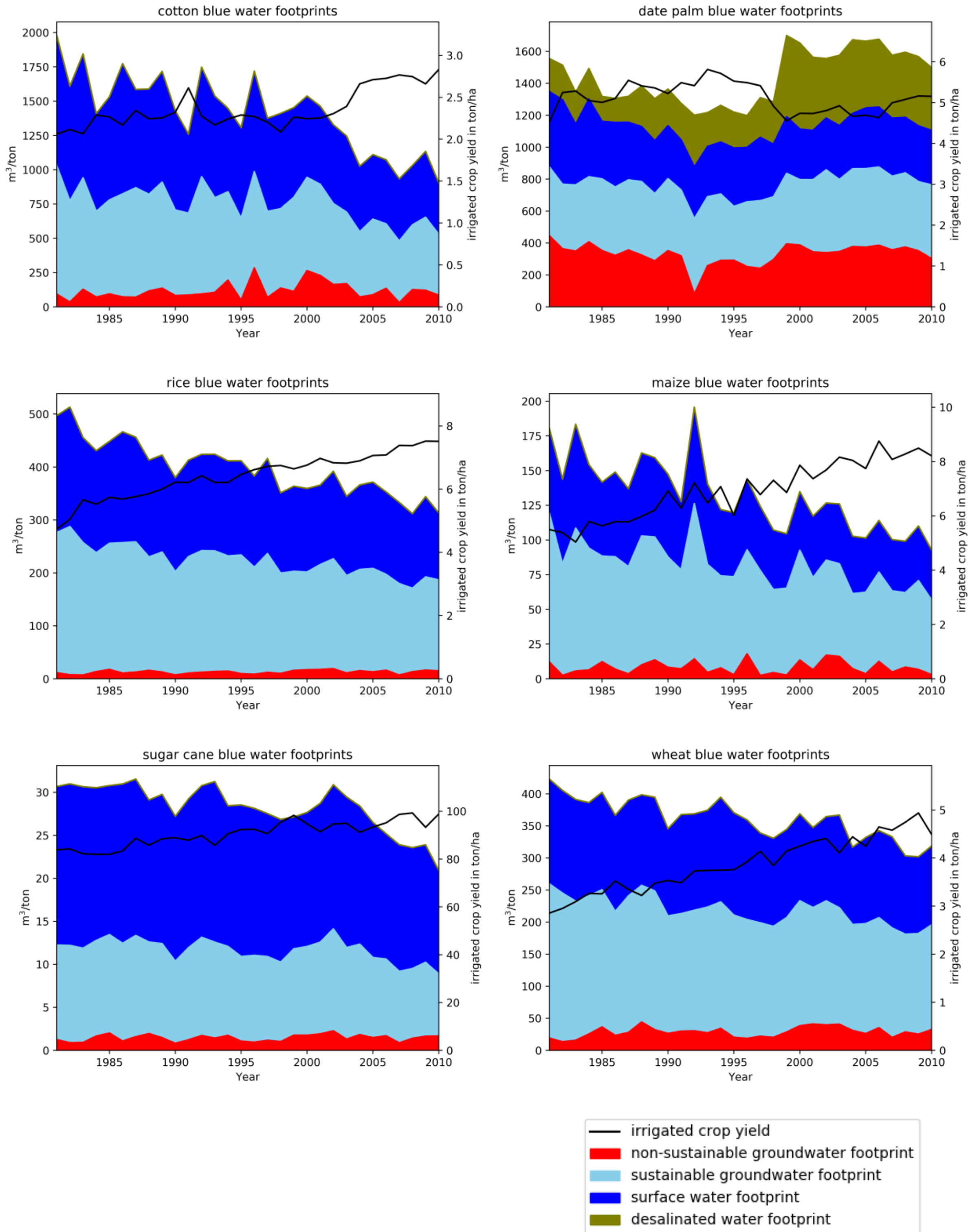


Figure 17 – Global average blue water footprints over time (left y-axis) and crop yield, being crop production in irrigated area divided by irrigated area (right y-axis) for selected crop types.

The total blue water footprint trends are mainly explained by an increase in crop yields in irrigated areas. This is also the case for maize, rice, soybeans, and wheat for blue (Hanasaki, 2016) and total water footprints (Hanasaki, 2016; Tuninetti et al., 2017). According to Hanasaki (2016) and Tuninetti et al. (2017), evapotranspiration plays a less important role than crop yields in temporal developments of global water footprints. Zhuo et al. (2014) show that blue water consumption is relatively sensitive to changes in precipitation. Aldaya et al. (2009), Grogan et al. (2015), Zoumides et al. (2013) and Starr & Levison (2014) show in case studies that in dry years, non-sustainable groundwater consumption increase.

Regionally, under prolonged dry periods in a changing climate, blue water consumption may increase sharply. Besides changes in climate, an even larger influence on total non-sustainable water consumption is expected to come from changes in irrigated area in the future. Assuming irrigated area and global crop production will continue growing, this will increase blue water consumption for agriculture (Yoshikawa et al., 2014). Furthermore, Foley et al. (2011) discusses that the increase in global crop yields slowed down over the past decades. When global crop production increases, while crop yields (ton/ha) increase less fast, total irrigated water consumption, and most probably non-sustainable groundwater footprints will increase in the future.

4. Discussion

In this section, the findings in this study are compared to other scientific literature. Limitations are discussed, and possible ways to reduce the non-sustainable groundwater consumption in this study are proposed.

4.1. Comparison with literature

This study presents a first global analysis on the consumption of surface water, desalinated water, sustainable groundwater, and non-sustainable groundwater by 24 crop types, both spatially, as well as over time during the period between 1981-2010. In this section, the findings from answering the three research questions are compared with literature.

In section 3.1. It was found that total irrigation withdrawals and consumption from irrigation in PCR-GLOBWB (565 km^3/yr and 297 km^3/yr respectively) stay behind by irrigation withdrawals and consumption from irrigation in Aqua21 (871 km^3/yr and 491 km^3/yr respectively), possibly due to different soil water balances and irrigation water requirements in both models. Using PCR-GLOBWB with the same climate forcing as the PCR-GLOBWB-run used here, while using other irrigated area quantities, Sutanudjaja et al. (2018) find an average irrigation plus livestock withdrawal of 2309 km^3/yr (Table 2). This raises the expectation that using the Aqua21 irrigated area input, which for the year 2000 contained only two-third of the irrigated area used in the run by Sutanudjaja et al. (2018), has a significant influence on the irrigation withdrawal in PCR-GLOBWB. The total irrigation withdrawal in PCR-GLOBWB in this study is an expected to be an underestimation, compared to other studies in Table 2, which range from 1078 to 3185 km^3/yr. Likewise, consumption from irrigation is probably an underestimation as well.

In section 3.2, the contribution of surface water, desalination, non-sustainable groundwater and sustainable groundwater to blue water consumption and the blue water footprint of crops is quantified. Döll et al. (2012) and Döll et al. (2014) found a groundwater fraction of 43% of the water consumption from irrigation during the period 1998-2002. Siebert et al. (2010) found a global groundwater consumption from irrigation of 43% of the total consumptive irrigation water use as well, compared to one third of the total consumption from irrigation in the research presented here (Table 2). Wada et al. (2012) found a global contribution of non-sustainable groundwater withdrawal to total irrigation withdrawal of 18%, Hanasaki et al. (2018) estimated this percentage to be 7%. Here, for consumption, the share of non-sustainable groundwater in total irrigation is 9%. This is close to the value found by Hanasaki et al. (2018) for withdrawal. Due to the likely underestimation of consumption from irrigation in PCR-GLOBWB due to irrigation water requirements, and lower irrigated area discussed above, The total non-sustainable groundwater consumption of 47 km^3/yr stays well below values found in other studies, see Table 2. Another reason for the low non-sustainable groundwater consumption could be the large share of capillary rise in blue water consumption, which causes a relatively small demand for irrigation in Aqua21. Differences in the calculation of blue water consumption play a role as well. Differences in total water consumption arising from different crop coefficients throughout a growing season and planting dates can have a large influence on blue water consumption (Zhuo et al., 2014). Furthermore, the share of water consumption satisfied with irrigation could be different between models, because of different algorithms which determine when soil water is depleted enough to start irrigation and different soil water content due to deep percolation and capillary rise.

Table 2 - Comparison of groundwater withdrawal and consumption for agriculture between different studies. All values are in km^3/yr. Irr = irrigation. Gw = groundwater. Gw non-sust is non-sustainable groundwater. Studies marked with an * add non-local water sources to non-sustainable groundwater. Note that for most studies in this table, blue water consumption and consumption from irrigation refer to the same flux. Only Hogeboom (2019) and the study presented here explicitly define blue water consumption and consumption from irrigation differently.

	Withdrawal			consumption					
Study	Irr	Gw	Gw non-sust	Blue	Irr	Gw	Gw non-sust	Model	Year
Rost et al. (2008) *	2555		1394	1364			728	LPJmL	Average 1971-2000
Hanasaki et al. (2010) *				1530			703	H08	Average 1985–1999
Siebert et al. (2010)					1277	545		GCWM	Around 2000
Siebert & Döll (2010)				1180				GWCM	Average 1998-2002
Mekonnen & Hoekstra (2010, 2011)				899				CROPWAT	Average 1996-2005
Wada et al. (2012)	1338		234					PCR-GLOBWB	The year 2000
Döll et al. (2012)	3185	1337.7			1231	529.3		WaterGAP	Around 2000
Döll et al. (2014)	1700	493			800	336		WaterGAP	Avg 2003-2009
Wada et al. (2014)	2885				1179			PCR-GLOBWB	The year 2000
Wada & Bierkens (2014)	2644				1392			PCR-GLOBWB	The year 2000
							194.7	PCR-GLOBWB	Around 2000
Dalin et al. (2017)							241.4	PCR-GLOBWB	Around 2010
Hanasaki et al. (2018)	2544	551	169		1368			H08 (Enhanced)	The year 2000
Sutanudjaja et al. (2018)	2309							PCR-GLOBWB	Average 2000-2015
Hogeboom (2019)				938				Aqua21	Average 1996-2015
	565				294			PCR-GLOBWB	Average1981-2010
This study	871			816	491	483	47	Aqua21 & PCR-GLOBWB	Average1981-2010

The contribution of different countries in global non-sustainable groundwater consumption differs between studies. In Dalin et al. (2017), groundwater depletion for agriculture in India is about 4.5 times as much as for the US in the year 2000, whereas the relative difference between these countries is less pronounced in the study presented here. For the year 2000, Wada et al. (2012) and Siebert et al. (2010) list China in the top-3 of agricultural non-sustainable groundwater consumers for the year 2000, whereas Dalin et al. (2017) (year 2000) and the study presented here (1981-2010 average) find a less important contribution to global non-sustainable groundwater consumption in China. It should be noted that the irrigated area dataset from Aqua21 used in this research contains half of the irrigated area as the MIRCA-dataset used as input for the study by Dalin et al. (2017) for reference year 2000. The difference in irrigated area is especially large in the North China Plains, an area in which Gleeson et al. (2012) find large non-sustainable groundwater abstractions. Although non-sustainable groundwater consumption volumes per crop and country found in Dalin et al. (2017) are substantially different than consumption volumes found here, the shares per crop for the main non-sustainable consuming countries USA, India, and Pakistan match well.

The country-specific non-sustainable groundwater footprints (m^3/ton) found for a few main crops and a few important countries are compared in Table 3 with results found in other studies. Especially for India and Pakistan, the differences tend to become large. For China, the absolute differences are relatively small, but relatively, the non-sustainable groundwater footprints calculated with other PCR-GLOBWB-runs by Bierkens et al. (2019) and Dalin et al. (2017) are about or more than ten times as large as the values found here. Again, this is expected to be mainly due to difference in irrigated area between the model-runs used.

Table 3 - Comparison of non-sustainable water footprints with literature, all in m^3/ton. Bierkens et al. (2019) reported crop yield (kg/ha/yr) and non-sustainable groundwater consumption (m^3/ha/yr), which are divided here to obtain non-sustainable water footprints (m^3/ton).

Country	**Crop**	**This study 1981-2010**	**Bierkens et al. (2019) 1971-2010**	**Dalin et al. (2017) 2000**
China	Wheat	3	26	31
	Maize	3	28	13
	Rice	2	55	27
India	Wheat	85	322	331
	Maize	5	62	16
	Rice	32	92	137
Pakistan	Wheat	173	830	499
	Maize	70	650	395
	Rice	302	1340	1245
USA	Wheat	26	6	29
	Maize	15	2	9
	Rice	11	45	70

Section 3.3 showed long-term trends and interannual variability in the contribution of non-sustainable groundwater to the blue water footprint of crops. The slight increase in blue water consumption of 1 km^3 per jaar found here does not match with the larger increases in irrigation water withdrawal found in Wada et al. (2012) and Wada and Bierkens (2014), showing increases in irrigation withdrawal between 1981 and 2000 and 1981 and 2010 of more than 20%. Wada et al. (2012) made use of the same climate input data as the study presented here. The differences with these studies could be explained partly with their use of other input datasets for irrigation.

4.2. Limitations

Although the research provided here shows potential, several important limitations should be considered when interpreting the results.

First, the share of non-sustainable groundwater in the blue water footprint of crops is likely an underestimation, as stated above. This limitation has consequences for the calculated share of non-sustainable groundwater in the blue water footprint of crops, globally and nationally, especially in regions where a substantial amount of sustainable groundwater is available next to non-sustainable groundwater, due to recharge.

In this study, groundwater consumption is only seen as non-sustainable when exceeding long-term recharge. However, consumption of other blue water sources and even green water consumption can be regarded as non-sustainable as well when exceeding environmental flow limits (Mekonnen & Hoekstra, 2020; Schyns et al. 2015). As proposed by Chouchane et al. (2015) and Dalin et al. (2019), a combined surface water, groundwater and green water sustainability assessment could inform on the overall sustainability of water consumption. Furthermore, adding such a distinction between green, and different types of blue water could show where groundwater can be pumped sustainably to alleviate pressure on scarce surface water (Altchenko & Villholth, 2015). This analysis could benefit from using a finer temporal resolution than the annual scale used in the research here, as water scarcity in water basins changes throughout a year (Hoekstra et al. 2012).

Another limitation is posed by the fact that fodder grasses are not included in the Aqua21 modelling framework and crops from the MIRCA 'others annual' crop class (see Appendix B) are not present in PCR-GLOBWB, meaning that these crops are not included in this research, while accounting for a combined 10% of the irrigated area in the MIRCA2000 dataset by Portmann et al. (2010). According to Esnault et al. (2014), fodder grasses play an important role in non-sustainable groundwater consumption in the High Plains aquifer.

The incongruity in the models used causes a limitation when it comes to modelling paddy rice. In Aqua21, rice is modelled like every other crop type, without adding water on top of the soil. Paddies need more irrigated water than bare soil, due to extra open water evaporation. This increased irrigated water consumption is not included. Whereas Aqua21 shows capillary rise to rice fields, which can only take place in non-saturated soils, paddy fields are saturated in reality. The sustainable groundwater consumption for paddy rice in this research is thus likely an overestimation.

Lastly, in this study, ratios of non-sustainable groundwater, sustainable groundwater, surface water and desalination are found by aggregating both irrigation and non-irrigation water consumption over abstraction zones in PCR-GLOBWB, which can reach up to 100 km^2 in size. These ratios are imposed on gridded blue water consumption patterns for different crops in Aqua21 within an abstraction zone (see Appendix A). The datasets used do not allow for specific gridded ratios per crop type, thus in the current results for example, relatively large groundwater consumption from industries within an abstraction zone will lead to higher groundwater ratios, thus higher contribution of groundwater to the total blue water footprint of crops in the results presented here. Likewise, a large non-sustainable groundwater consumption for one irrigated crop type will influence the non-sustainable groundwater contribution to the blue water footprint for all irrigated crops in an abstraction zone in this study.

4.3. Reducing non-sustainable groundwater consumption

In the decades to come, a changing climate is expected to bring prolonged dry periods regionally, leading to more groundwater consumption (Scanlon et al., 2012). Furthermore, decelerating increases in crop yields (Foley et al. 2011) and expanding irrigated areas (Yoshikawa et al., 2014), can lead to increasing non-sustainable groundwater consumption (Foley et al., 2011; Scanlon et al., 2012; Wada et al., 2012). Different combined strategies may help reducing non-sustainable groundwater footprints, despite growing demand for crop production. From a governance perspective, water pricing mechanisms and groundwater abstraction caps are proposed by several scholars (Bierkens & Wada 2019). From a producer's perspective, choosing water efficient crops can decrease the pressure on groundwater (Aldaya et al., 2009). Practices which enhance irrigation efficiency can have its benefit as well (Chukalla et al., 2015). Zhuo et al. (2016b) and Sun et al. (2013a) advice to grow crops which growing seasons are adjusted to the precipitation pattern within a region, to efficiently make use of green water. From a consumer's or importer's point of view, deciding where to obtain crop products to alleviate pressure on groundwater resources can have its effects as well. Importing cotton from water-rich Brazil instead of from the over-exploited Indian Upper-Ganges aquifer can decrease non-sustainable groundwater consumption in that region. Hoekstra (2017a) and Marston et al. (2015) point out that a large portion (up to 40%) of the non-sustainable groundwater embedded in products derived from crops fed with water from USA-aquifers is used for meat production. Decreasing demand for meat and shifting diets can have a large influence on water consumption and hence on reducing groundwater depletion (Ercin & Hoekstra, 2014).

5. Conclusions and recommendations

5. Conclusions and recommendations

In this chapter, conclusions are drawn, and recommendations are proposed.

5.1. Conclusions

The objective for this study was to quantify the spatial distribution of, and interannual variability and trends in the contribution of groundwater, surface water and desalinated water to the blue water footprints of crops, globally at a high spatial resolution (5x5 arcmin), with a focus on the role of non-sustainable groundwater consumption for crop production.

First, it was analysed whether irrigation withdrawal and consumption patterns in Aqua21 and PCR-GLOBWB are in agreement. Both models show the same top-consuming areas. However, the differences in irrigation withdrawal, as well as consumption from irrigation between PCR-GLOBWB and Aqua21 are large: both global PCR-GLOBWB withdrawal for irrigation and consumption from irrigation are 40% larger than Aqua21 withdrawal for irrigation and consumption from irrigation, possibly due to differences in the modelling of irrigation water requirements. Blue water consumption in PCR-GLOBWB is expected to be an underestimation, which means that found non-sustainable groundwater consumption for crops is expected to be lower than expected from other literature, especially in areas where other sources than non-sustainable groundwater consumption are present.

Secondly, it is calculated that for all 24 crop types assessed, the average total blue water consumption over 1981-2010 was 816 km^3/yr, of which 47 km^3/yr (6%) came from non-sustainable groundwater. Large non-sustainable groundwater consumption was found for the crops wheat, rice, maize and cotton. Date palm and cotton have both the largest total blue and non-sustainable groundwater footprints (m^3/ton). The largest share of worldwide non-sustainable groundwater consumption takes place in India, the USA and Pakistan. The ratio of non-sustainable groundwater to total blue water consumption is the largest for the aquifers underlying these countries, as well as for regions in North Africa and the Middle East. Top-producing countries show large differences in quantity and composition of the blue water footprint of crop types.

Answering the third research question, the global non-sustainable groundwater consumption by crops increased slightly over the period between 1981-2010, with a trend of 1.0 km^3/yr, mainly driven by increases in non-sustainable groundwater consumption for wheat, rice, and cotton production. For most crops, non-sustainable groundwater footprints decreased. Long-term trends in consumption and footprints were mainly due to changes in irrigated area (consumption) and crop yields (footprints), whereas evapotranspiration of non-sustainable groundwater did have a smaller effect on the overall trend but did have effects on interannual variability.

Concluding, the average share of non-sustainable groundwater in the blue water footprint of global crop production is 6%. Global non-sustainable groundwater consumption increased slightly over time, while non-sustainable groundwater footprints for different crops decreased.

5.2. Recommendations

Under a growing demand for crops and a changing climate, non-sustainable groundwater consumption and footprints for crops are expected to increase. However, reducing groundwater withdrawal for irrigation can reduce pressure on groundwater resources. This can be achieved by supply-side changes in crop composition or making use of efficient irrigation practices. On the demand-side, water saving by choosing to consume less crops and crop-derived products from areas with non-sustainable groundwater footprints can make an important difference.

For further research into non-sustainable groundwater consumption related to global crop production, based on the methodology and discussion of the results, the following recommendations can be made:

First, it was within the scope of this research to harmonize PCR-GLOBWB and Aqua21 and to assess to what extent irrigation withdrawal and consumption from irrigation in both models are in agreement, but not what reasons are behind differences in irrigation withdrawal and consumption. In the discussion section, possible reasons are explained. It is recommended to quantify the sensitivity of blue water consumption in both models to actual evapotranspiration, deep percolation and capillary rise and the influence of the length of growing seasons. This may also improve the understanding of the large role that capillary rise plays in the global blue water footprint of crops.

Secondly, it is recommended to include crop water consumption per blue water source in a broader analysis on the sustainability of groundwater, surface water and green water, combined with scarcity of different water sources, at a monthly instead of an annual resolution. Such an analysis can for example inform on where groundwater can be pumped sustainably to alleviate pressure on scarce surface water, or when consumption of blue water from capillary rise is sustainable, regarding water scarcity.

Thirdly, A full integration of a crop growth model with a global hydrological model enables for tracing back the origins of crop water consumption directly per crop, instead of applying ratios based on total consumption of all crop types and non-irrigation sectors combined, over abstraction zones up to 100km^2.

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Appendices

Appendix A: Introduction into PCR-GLOBWB and Aqua21

PCR-GLOBWB

PCR-GLOBWB essentially solves a global water balance for the terrestrial part of the water cycle. On a daily basis, the interaction between natural and human-induced water flows is assessed. The model consists of gridded stacks of two soil layers and a groundwater layer (see Figure 18).

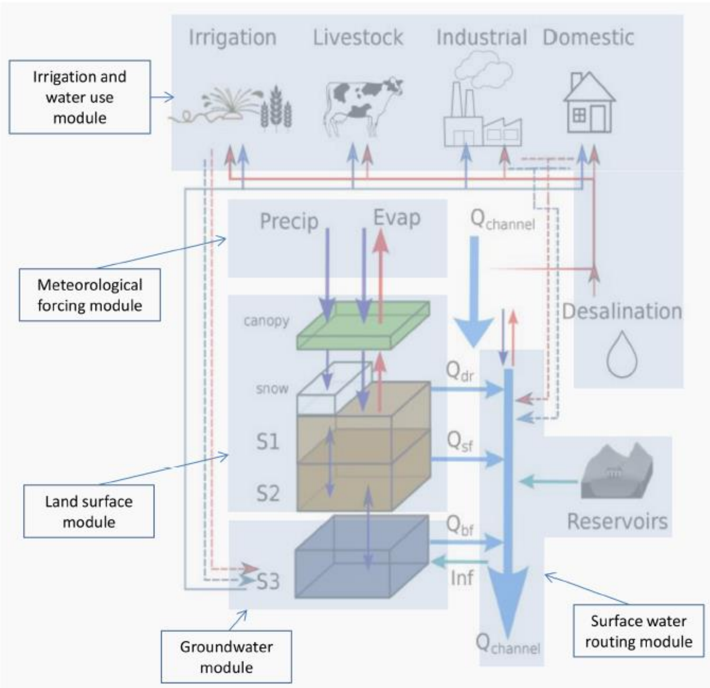

Figure 18 - Schematization of PCR-GLOBWB (Sutanudjaja et al., 2018).

In the irrigation and water use module, amongst others, the irrigation water demand is calculated. To do this, first the crop water consumption is assessed. Reference evapotranspiration is calculated using the Penman-Monteith equation. Actual crop evapotranspiration is calculated according to FAO-guidelines (Allen et al., 1998), using crop-coefficients and rooting depths derived from Siebert & Döll (2010) and cropping calendars by Portmann et al. (2010) (Wada et al., 2014).

Secondly, in a soil water balance, irrigation water demand is calculated using two different algorithms for paddy rice fields and non-paddy crops (Wada et al., 2014). For paddy rice, a 50 millimetre surface water depth is maintained until the late crop development stage before harvest. For non-paddy crops, irrigation water is applied up to field capacity when readily available water falls below total available water multiplied with a soil water depletion factor which is a function of crop evaporation and a reference soil water depletion fraction. Other terms in the soil water balance include water exchange with deeper soil layers through infiltration and capillary rise, crop evapotranspiration and precipitation. Runoff is assumed to be absent when irrigating (Wada et al., 2014).

Thirdly, multiplication with a country-specific irrigation conveyance efficiency factor by Rohwer et al. (2007) yields the irrigation water withdrawal for the crop types 'irrigated paddy', 'irrigated non-paddy' and 'rainfed'.

Together with water withdrawal for the industries, households and livestock, irrigation water withdrawal makes up the total water withdrawal. Water demand for each sector is calculated on a 5x5 arcminute grid on a daily basis.

Because water consumers can withdraw their water sources outside the 5x5 grid cell (which roughly equals 10x10 km at the equator), available water and water demand are pooled and compared over so-called abstraction zones, see Figure 19. In the model run used here, in line with Hofste et al. (2019), the abstraction zones are 1x1 arcminute cells, truncated by countries and watersheds.

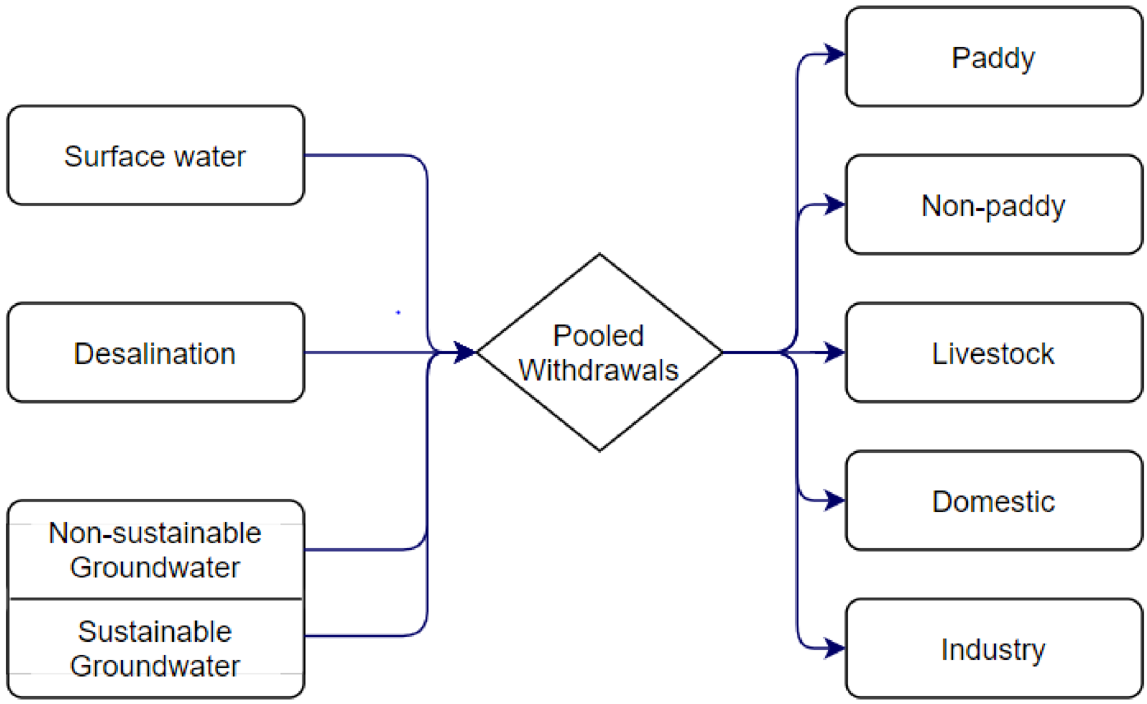

Figure 19 - Schematical visualisation of pooling over abstraction zones in PCR-GLOBWB.

The allocation of the pooled water demand over the different sources of water happens as follows. First, all available desalinated water is consumed. Then, readily available surface water is determined based on water in channels in a grid cell. Following a dynamic allocation scheme by De Graaf et al. (2014), the availability of surface water or groundwater for abstraction is determined based on the ratio between two-year running averages of baseflow and discharge within grid cells. This ratio serves as a proxy to determine how abundant water sources are in a cell, and thus what would be a logical source to abstract water from. In case of irrigation, ratios of surface water and groundwater abstractions by Siebert et al. (2010) are prioritized when these ratios are deemed reliable (Sutanudjaja et al., 2018). The available surface water is used next, considering a minimum available surface water of 10% of annual average discharge under natural flow conditions. The remainder of the water demand is satisfied with groundwater. Groundwater abstractions are capped by pumping capacity based on data from the IGRAC GIS database (Sutanudjaja et al., 2018). In PCR-GLOBWB, changes in groundwater storage are calculated by abstracting groundwater abstractions from percolation, riverbed infiltration and return flows from irrigation. When the storage layer within PCR-GLOBWB becomes negative, due to persistent groundwater withdrawal, part of the groundwater demand is abstracted from non-sustainable groundwater resources (De Graaf et al., 2014).

Aqua21

Within the Aqua21 modelling framework, the AquaCrop crop growth engine is used to calculate crop evapotranspiration and crop yields. AquaCrop is a water-driven crop water productivity model (Steduto et al., 2009). Based on climate data, crop characteristics, soil profiles and management practices, it determines crop yield and crop water consumption, but also other parts of a soil water balance, such as irrigation demand, capillary rise, and runoff. Within AquaCrop, the development of a canopy cover is calculated. Canopy growth is influenced by temperature and can be hampered by stress factors due to water shortages, water logging, low or high temperatures and soil salinity (Raes, 2017).
Crop evaporation and transpiration are calculated by multiplying the reference evapotranspiration calculated with the Penman-Monteith equation (Allen et al., 1998) with a crop coefficient proportional to the canopy cover. Hampered crop growth influences crop yield, but also crop evapotranspiration. Crops are able to die, and thus stop using water as well. In Aqua21, a shadow water balance is used to determine the fractions of crop evapotranspiration coming from blue water by irrigation or capillary rise, as well as green water from precipitation, following the method by Chukalla et al. (2015).

In Aqua21, full irrigation is assumed. When readily available water is depleted more than 30%, irrigation water is applied up to field capacity (depletion = 0%). The irrigation water applied corresponds with the 'irrigation amount that has infiltrated in the field. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field [are not] added.' (Raes, 2017). Still, it may occur that irrigated water added to the soil may percolate to the ground.

Within Aqua21, sowing days are obtained from Portmann et al. (2010). Harvested dates are calculated dynamically within AquaCrop. Soil data is obtained from De Lannoy et al. (2014). Groundwater tables in order to calculate capillary rise are obtained from Fan et al. (2013).

Appendix B: Crop classes

The following table shows the 59 crops which are modelled in Aqua21, their FAOSTAT crop code, the corresponding MICRA2000 crop code and crop name and the crop category used in PCR-GLOBWB in the WRI Aqueduct run. Note that PCR-GLOBWB does not include the MIRCA class 'others annual'.

Table 4 – Crops modelled in Aqua21 with FAOSTAT crop names and crop codes, with matching MIRCA2000 crop classes and crop codes, and PCR-GLOBWB class.

Faostat code	Faostat name	Mirca code	Mirca name	PCR-GLOBWB class
15	Wheat	1	Wheat	Non-paddy
56	Maize	2	Maize	Non-paddy
27	Rice, paddy	3	Rice	Paddy
44	Barley	4	Barley	Non-paddy
71	Rye	5	Rye	Non-paddy
79	Millet	6	Millet	Non-paddy
83	Sorghum	7	Sorghum	Non-paddy
236	Soybeans	8	Soybeans	Non-paddy
267	Sunflower seed	9	Sunflower	Non-paddy
116	Potatoes	10	Potatoes	Non-paddy
125	Cassava	11	Cassava	Non-paddy
156	Sugar cane	12	Sugar cane	Non-paddy
157	Sugar beet	13	Sugar beet	Non-paddy
254	Oil palm fruit	14	Oil palm	Non-paddy
270	Rapeseed	15	Rapeseed	Non-paddy
242	Groundnuts, with shell	16	Groundnuts	Non-paddy
176	Beans, dry	17	Pulses	Non-paddy
187	Peas, dry	17	Pulses	Non-paddy
195	Cow peas, dry	17	Pulses	Non-paddy
203	Bambara beans	17	Pulses	Non-paddy
210	Lupins	17	Pulses	Non-paddy
490	Oranges	18	Citrus	Non-paddy
577	Dates	19	Date palm	Non-paddy
560	Grapes	20	Grapes	Non-paddy
328	Seed cotton	21	Cotton	Non-paddy
661	Cocoa, beans	22	Cocoa	Non-paddy
656	Coffee, green	23	Coffee	Non-paddy
221	Almonds, with shell	24	Others perennial	Non-paddy
249	Coconuts	24	Others perennial	Non-paddy
260	Olives	24	Others perennial	Non-paddy
486	Bananas	24	Others perennial	Non-paddy
489	Plantains and others	24	Others perennial	Non-paddy
515	Apples	24	Others perennial	Non-paddy
521	Pears	24	Others perennial	Non-paddy
534	Peaches and nectarines	24	Others perennial	Non-paddy

Table 4 – continued

Faostat code	Faostat name	Mirca code	Mirca name	PCR-GLOBWB class
547	Raspberries	24	Others perennial	Non-paddy
571	Mangoes, mangosteens, guavas	24	Others perennial	Non-paddy
574	Pineapples	24	Others perennial	Non-paddy
75	Oats	26	Others annual	-
94	Fonio	26	Others annual	-
97	Triticale	26	Others annual	-
108	Cereals nes	26	Others annual	-
122	Sweet potatoes	26	Others annual	-
137	Yams	26	Others annual	-
358	Cabbages and other brassicas	26	Others annual	-
372	Lettuce and chicory	26	Others annual	-
373	Spinach	26	Others annual	-
388	Tomatoes	26	Others annual	-
394	Pumpkins, squash and gourds	26	Others annual	-
397	Cucumbers and gherkins	26	Others annual	-
401	Chillies and peppers, green	26	Others annual	-
403	Onions, dry	26	Others annual	-
406	Garlic	26	Others annual	-
414	Beans, green	26	Others annual	-
417	Peas, green	26	Others annual	-
426	Carrots and turnips	26	Others annual	-
430	Okra	26	Others annual	-
567	Watermelons	26	Others annual	-
723	Spices nes	26	Others annual	-