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Influence of irrigation water use efficiencies on the sustainability of irrigation: interrelations of irrigation efficiency, water availability and irrigated area at the global scale

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Abstract

Irrigation water use is crucial to sustain food production in the context of growing population and globalization, yet is one of the main drivers of water scarcity and increased competition between water users. This study evaluates the influence of irrigation water use efficiencies on the sustainability of irrigation by examining trends in irrigation water requirements. The PCR-GLOBWB model is run to simulate water availability and irrigation water demand over the historical period 1960-2010, using climate drivers from the CRU-TS 3.21 meteorological data set, and over the 21st century (2006-2099), using three climate projections from the HadGEM2-ES, the IPSL-CM5A-LR, and the GFDL-ESM2M global climate models. Irrigation water demand is estimated under a scenario of irrigation efficiency improvement based on future development of irrigation efficiency described by *Fischer et al*. [2007] and country-specific irrigation project efficiency compiled by *Rohwer et al*. [2007].

The results show that the global volume of irrigation water use significantly increased over the historical period, stabilizes around 2020, and slightly decreases until the end of the 21st century. Irrigated area expansion is the main driver of the significant increase in past irrigation water requirements. The results vary significantly over the 21st century, depending on the climate projection used. Our projections do not account for future irrigated area expansion due to the deficiency in qualitative and quantitative projections of land use change; hence results are mainly driver by climate variability (i.e., climate change).

The results indicate the necessity of pursuing irrigation water use efficiency improvement and that such development will play a large role to reduce the pressure of irrigation water use on water resources.

Keywords: Macro-scale hydrological PCR-GLOBWB; Water availability; Crop water requirements; Irrigation water efficiencies

Preface

This document is my Master Research thesis (GEO4-1520, 30 ECTS) I worked on during my Msc study, Earth, Surface and Water Sciences, Hydrology track. I hope you appreciate it.
This thesis is my first experience with water abstractions and irrigation efficiency. Over time, it proved it was a very nice and enriching experience. Like most scientific work, my study had ups and downs. However, I truly enjoyed participating in the development of the global hydrological scale PCR-GLOBWB model, as it helped me to develop further my knowledge on hydrological processes.
Finally, I want to thank my supervisor, Dr Rens Van Beek, for his invaluable support before and during my master research, and my second supervisor, Dr Yoshihide Wada, for his support and great advices during my work. I also want to thank my parents and my fiancée for their understanding and their support throughout the development of my study.

Romain Merlevede
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1. Introduction

1.1 Background and problem description

Water has always been the main limiting factor for crop production in regions of the world where rain water is insufficient to satisfy crop water requirements [*Food and Agriculture Organization (FAO) Irrigation and Drainage Paper 66*, 2012]. The rise in consumptive irrigation water use presents a crucial challenge for human society. With 70 %, irrigation forms the most important constituent of human water needs and it has risen significantly since the beginning of the 20th century; also, irrigated crops become more vital in ensuring global food security [*Johnson et al*., 2001; *Abdullah*, 2006]. This rise can be explained by the combined effects of a growing population and increased living standards. Competition for water resources has become even more severe as a result of globalization and international food trade. However, according to the Millennium Ecosystem Assessment, between 15 and 35 % of irrigation withdrawals are unsustainable (i.e., long-term groundwater recharge or freshwater supply rates are exceeded by irrigation withdrawals) [*United Nations Environment Programme* (*UNEP*), 2005]. In addition, most large-scale irrigation systems are described as inefficient with ~ 60 % of water diverted or withdrawn for irrigation being wasted [*FAO*, 1990; *Clay*, 2004], and irrigation has long been described as a wasteful water use [*Bhatia and Falkenmark*, 1992]. With the global population expected to rise to 9 billion by 2050 [*United Nations (UN)*, 2009, 2013], it is essential that the efficiency of irrigation water use, defined as the ratio of irrigation water consumption to the amount of total water withdrawn, transported, distributed, and applied at the field scale, is increased to reduce water losses and water demand, attain higher yields, and improve the water productivity. Irrigation water efficiency improvements can lower human pressure on environmental flow and associated ecosystems and reduce ecological stress, while helping to increase the reliability of water supply in the context of climate change and growing uncertainty of future water resources availability. Increasing water scarcity and competition for water resources can be alleviated by realizing improvements in irrigation water efficiencies, which in turn can help to increase water productivity by optimizing the transport and application of water to the crops. Increases in the efficiency of technologies and infrastructures for water supply have helped to secure agricultural production by increasing on-farm irrigation efficiencies and to address the growing food demand issue [*Liu et al*., 2002; *Scheierling et al*., 2004]. However, improved on-farm irrigation efficiencies increase the willingness and ability of an irrigator to purchase irrigation water, which may lead to a higher water demand and consumption [*Contor and Taylor*, 2013]. Furthermore, the network of facilities and systems for irrigation water supply is rarely the same from one river basin to another.

1.2 Irrigation in the global hydrological cycle

During the 20th century, increasing human population and living standards led to a substantial rise in food demand. This has resulted in a considerable increase of water demand for the agriculture (i.e., irrigation and livestock) and in the expansion of irrigated areas. Irrigation is critical to food security as it maximizes crop yields. Irrigation equipped areas represent only ~ 20 % of total cultivated land, however they contribute to ~ 40 % of the global food production [*Abdullah*, 2006]. Livestock water demand ranges from 1 to 2 % of total water withdrawal while irrigation water abstractions represent more than 70 % of total water withdrawal [*Shiklomanov*, 2000a; *Johnson et al*., 2001; *Wada et al*., 2011b; *Wada et al*., 2014]. Other water demand sectors are the domestic (i.e., households and municipalities) and the industrial sectors that account for 13 % and 18 % of total water withdrawal, respectively. Clearly, agriculture is by far the largest water demand sector, mostly due to irrigation.

Figure 1.1, from the work of *Oki and Kanae* [2006], presents the anthropogenic effects on global natural hydrological fluxes and storages. Globally, irrigation equipped areas were covering about 0.53 million km^2 yr^{-1} in 1901, whereas irrigated areas were representing about 3 million km^2 yr^{-1} around the year 2000 [*Rockström et al.*, 2007a; *Freydank and Siebert*, 2008; *Wisser et al*., 2010; *Portmann et al*., 2010]. Nevertheless, irrigated areas are not expected to increase significantly in the next few decades, due to limitations in land and water availability [*Faures et al.*, 2002; *Bruinsma*, 2003; *FAO*, 2006a; *Alexandratos and Bruinsma*, 2012]. Over the period 1960-2000, gross and net irrigation water demands have more than doubled, representing ~ 80 % of the contemporary total gross and net water demands [*Döll and Siebert*, 2002; *UNEP*, 2005; *Wisser et al*., 2010; *Wada et al*., 2011b]. Global net irrigation blue water (i.e., surface water and renewable groundwater resources) demand has increased from 590 km^3 yr^{-1} in 1901 to a contemporary global volume that satisfies the maximum crop-specific transpiration and ensures optimal crop growth ranging from 1092 km^3 yr^{-1} to 1364 km^3 yr^{-1}. Total gross irrigation blue water demand ranges from 2254 km^3 yr^{-1} to 3100 km^3 yr^{-1} (see 'irrigated cropland' in Fig. 1.1) [*Döll and Siebert*, 2002; *Vörösmarty et al*., 2005; *Hanasaki et al.*, 2006; *Oki and Kanae,* 2006; *Siebert and Döll,* 2007; *Hanasaki et al*., 2008a,b; *Rost et al.*, 2008; *Wisser et al*., 2010; *Wada et al*., 2011b]. Total gross irrigation blue water demand accounts for the volume of water applied to prevent salinization and losses that occur during abstraction, transport, distribution, and application on the field scale. Irrigation is the main water consumptive activity, as livestock, domestic and industrial consumptions are comparably low: global agricultural water consumption ranges from 1200 to 1800 km^3 yr^{-1} and amounts to ~ 90 % of total water consumption [*Shiklomanov and Rodda*, 2003; *Vörösmarty et al*., 2005; *Rost et al.*, 2008; *Rockström et al.*, 2009; *Wada et al.*, 2011b; *Wada et al.*, 2014]. Figure 1.2, from the United Nations World Water Development Report 2, shows the distribution of water use in the world, in regions with contrasting economic development and among sectors [*UN*, 2006].

The objective of irrigation is to provide adequate amounts of water into the soil to satisfy crop water requirements, sustain full crop growth by enabling maximum crop transpiration (which is function of the local climate, plant cover and stage of growth [*Perry et*

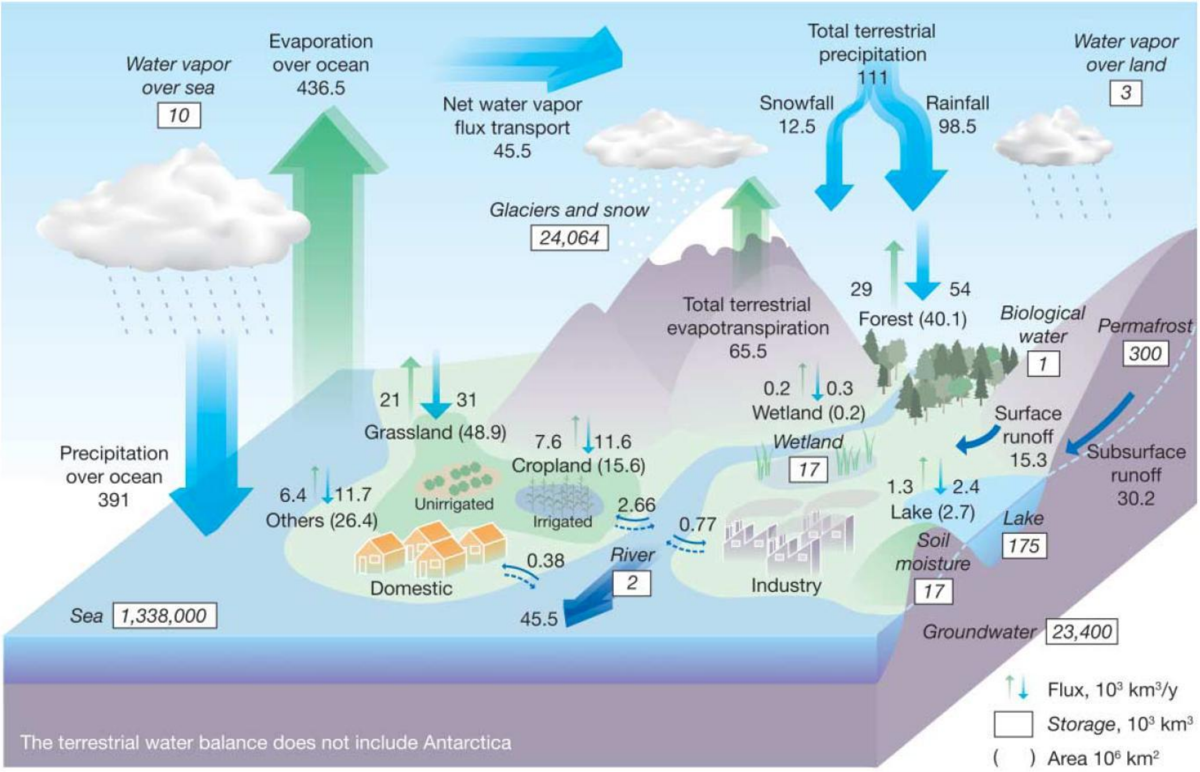

Figure 1-1: Global hydrological fluxes (1000^3 km^3/year) and storages (1000 km^3) with natural and anthropogenic cycles. Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean, which include annual precipitation and evapotranspiration over major landscapes presented by small vertical arrows; parentheses indicate area (million km^2). The direct groundwater discharge, estimated to be about 10% of total river discharge globally, is included in river discharge. From *Oki and Kanae* [2006].

al., 2009]), improve food supply to the population, support other human requirements (e.g., cotton needs for clothing production), and ultimately contribute to a better income for farmers. Productive vapour flows from cropland (i.e., crop transpiration) depend on the plant-available amount of green water (i.e., water from local rainfall infiltrated and stored in the root-zone of the soil minus runoff and evaporative losses) [*Rockström et al*., 2009]. Green water corresponds to the actual evapotranspiration without irrigation, that is, the sum of crop-specific actual evapotranspiration and actual bare soil evaporation [*Wada et al*., 2012a]. Irrigation water is supplied to complement green water available to cultivated crops. It is abstracted from available blue water resources of a given region: water available in rivers, lakes, artificial reservoirs, wetlands, and renewable groundwater [*Vörösmarty et al*., 2005; *Rost et al*., 2008; *Rockström et al*., 2009]. However, water supports services for life and ecosystem processes [*UNEP*, 2005]. *Smakhtin et al*. [2004] thus introduced a factor to account for environmental flow needs in the computation of irrigation water requirements.

Several definitions for irrigation efficiency exist, depending on the type of observer (e.g., hydrologist, farmer, and economist). To relate to the hydrological context, irrigation efficiency is discussed in terms of the “most widely accepted” definition of irrigation water efficiencies, as proposed by *Bos and Nugteren* [1990] [*SanaeeJahromi et al*., 2001; *Rohwer et al*., 2007], with a ratio of input to output inflow applied by irrigation systems to the crops, and irrigation efficiencies ranging from 0 to 1. Irrigation efficiency thus corresponds to the ratio of net to gross irrigation water requirements, with net irrigation water requirements taken as the supplementary amount of water needed to allow maximum potential crop

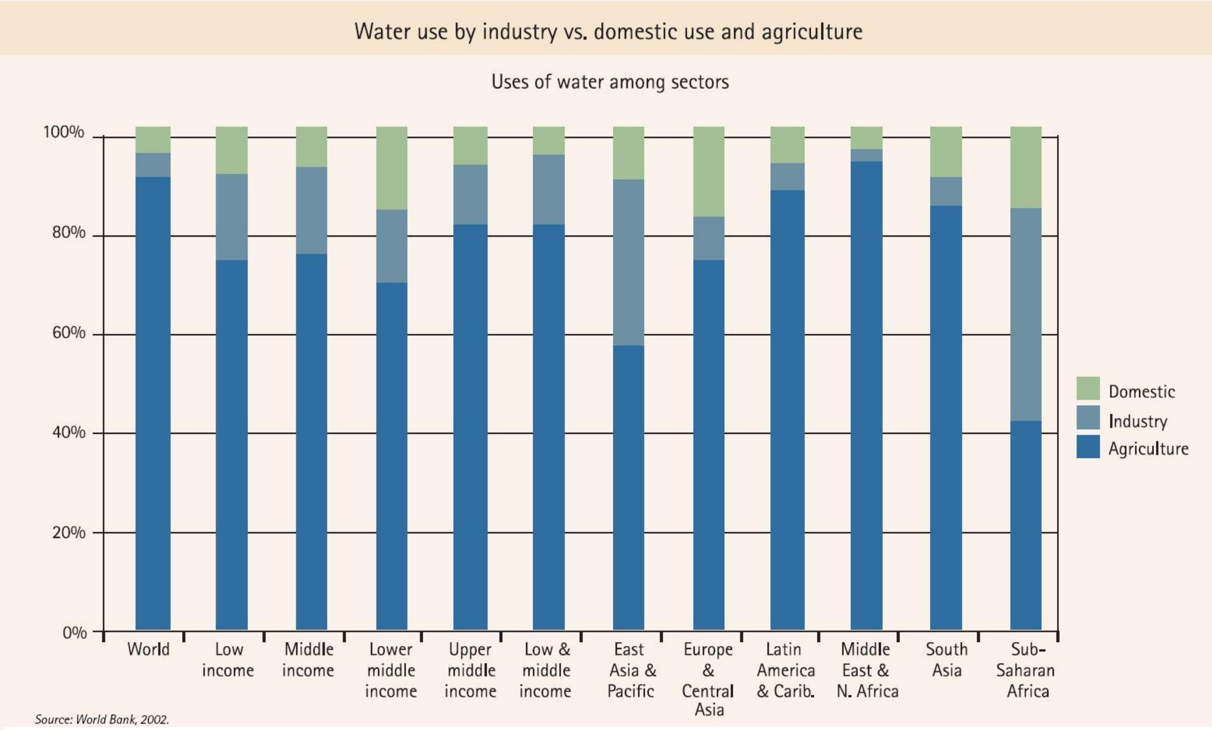

Figure 1-2: Distribution of water use in the world, in regions with contrasting economic development and among sectors. From the United Nations World Water Development Report 2 [*UN*, 2006].

transpiration, hence optimal crop growth, and with gross irrigation water requirements equated as the actual amount of water that needs to be withdrawn from the source, after taking into account all potential loss. Irrigation efficiency corresponds to the combination of the partial efficiencies of the components of an irrigation system: the conveyance (i.e., the ratio of the volume of water diverted or pumped from a source to the volume delivered to the distribution system), the distribution (i.e., the ratio of the volume of water delivered to the distribution system to the volume furnished to the fields), and the field application (i.e., the ratio of the volume furnished to the fields to the volume actually made available to the crops) efficiencies. Once combined, these partial efficiencies represent the overall or project efficiency which is described as the fraction of water abstracted or diverted from a source for irrigation purposes and made available for productive crop evapotranspiration [*Bos and Nugteren*, 1990; *Döll and Siebert*, 2002, *Rohwer et al*., 2007]. *Rohwer et al*. [2007] replaced the distribution efficiency factor by a field management factor due to the deficiency of data or low data reliability on distribution systems efficiency. This management factor ranges from 1 to 0.7, depending on the type of irrigation system used (i.e., surface irrigation, sprinkler, or micro-irrigation) and the scale of the irrigation system (i.e., from small to expended large scale systems).

In the context of agriculture, the concepts of water use efficiency (WUE, in kg m^{-3}), taken equal to Y/Tr, (with Y the yield or biomass in harvestable parts of the plant, in kg, and Tr the crop transpiration over the growth period, in mm or m^3) and irrigation water use efficiency (IWUE, in kg m^{-3}), calculated as Y/I, (with I the volume of irrigation water applied, in m^3) are commonly used in order to characterize the outcome of irrigation water application over the cultivated crops and to describe the effectiveness of irrigation [*Perry*, 2007; *Payero et al*., 2008]. Crop water production functions have been widely used to describe the relationship between crop yield and water input (i.e., rainfall, available green water and additional blue water provided by irrigation) and to determine optimal water application at the field scale.

Procedures developed in the sixties and seventies relating crop yield to the amount of water applied [*De Wit*, 1968; *Kassam*, 1977; *Hexem and Heady*, 1978; *Doorenbos and Kassam*, 1979] led to the FAO's yield response to water and yield to biomass ratio equations at the core of the AquaCrop growth model [*FAO*, 2012]: $B = WP \times \sum Tr$, and $Y = HI \times B$, where B is the biomass produced, Tr the crop transpiration summed over the growth period, WP the water productivity parameter, Y is the crop yield, corresponding to biomass in harvestable parts of the plant, and HI is the harvested index. The WP parameter is parameterized and normalized with the reference potential evapotranspiration ET_0, crop transpiration Tr and atmospheric CO_2 concentration. The water productivity is defined by the amount of crop yield per input water volume (in kg m^3 or kg ha^{-1} mm^{-1}). These equations, based on the consumptive use of water, or crop evapotranspiration, have been used to analyze crop response to water inputs and deficits [*Payero et al*., 2008], and the link between water productivity and crop yield (e.g., *Rost et al*. [2008], *Steduto et al*. [2009], *Raes et al*., [2009], *Siebert and Döll* [2010]).

However, *Bos and Nugteren* [1990] did not include crop yield and other criteria like financial returns compared to the volume of water applied as these do not actually reflect the effects of irrigation activities on the environment. In the same way, irrigation efficiency is described in this study by using irrigation water efficiencies from the global database of *Rohwer et al*. [2007]. Since water is used as a resource to produce consumer goods, it is interesting to study how improvements in irrigation efficiency have impacted the evolution of crop production during the last decades. Water productivity is discussed by considering the fraction of crop water requirements satisfied, looking at the effects of irrigation technology and water management on the gap between fully satisfied irrigation conditions and actual water supply, especially under water stress.

The components of irrigation blue water flows have to be considered and described separately in order to assess the efficiency of irrigation practices. First, a fraction of irrigation water made available to the crops is consumed. Irrigation water consumption encompasses the beneficial and non-beneficial consumption of water, that is, the transpiration from an irrigated crop and the evapotranspiration for unintended purposes (e.g., bare soil and open-water surfaces evaporation, riparian weeds transpiration), respectively. Blue water consumed for irrigation is considered lost to the atmosphere and not available for any other purposes [*Perry*, 2007]. Any remaining irrigation water goes to the non-consumed fraction, comprising a recoverable and non-recoverable fraction, that is, the return flows from irrigated areas to the environment (i.e., surface water bodies, and groundwater resources), and the flow of irrigation water lost to any further use (e.g., flows to saline water), respectively [*Falkenmark*, 2003; *Perry*, 2009; *Rockström et al.*, 2009]. In essence, green water flows consist of a consumptive use of freshwater only since it is not available for other purposes after transpiration for beneficial consumption and evapotranspiration for unintended uses [*Falkenmark*, 2003].

Although irrigation is necessary to secure the growing population food demand, water availability is limited. Annual discharge from continents to the oceans is comprised between 35000 km^3 yr^{-1} and 45500 km^3 yr^{-1}, and the estimated upper limit of accessible blue water resources ranges from 12500 $km^3\ yr^{-1}$ to 15000 $km^3\ yr^{-1}$ [*Baumgartner and Reichel*, 1975; *Postel et al*., 1996; *Postel et al*., 1998; *Vörösmarty et al*., 2000, 2005; *De Fraiture et al*., 2001; *Fekete et al*., 2002; *Döll et al*., 2003; *Oki and Kanae*, 2006]. *Rockström et al.* [2009] introduced the concept of planetary boundaries to define the safe operating space for humanity with respect to the earth system, including human freshwater use. Increases in runoff appropriation and associated shifts in volumes and patterns threaten human and aquatic ecosystems water needs. *Rockström et al.* [2009] proposed a planetary boundary for global freshwater use of 4000 $km^3\ yr^{-1}$ of blue water consumed, with a zone of uncertainty lying between 4000 $km^3\ yr^{-1}$ and 6000 $km^3\ yr^{-1}$. Contemporary blue water withdrawals are ~ 4000 $km^3\ yr^{-1}$, while ~ 2600 km^3 of blue water are consumed every year, with more than 70 % consumed for agricultural purposes [*Döll and Siebert*, 2002; *Shiklomanov and Rodda*, 2003; *Vörösmarty et al*., 2005; *Hanasaki et al.*, 2006; *Oki and Kanae*, 2006; *Siebert and Döll*, 2007; *Hanasaki et al*., 2008a,b; *Rost et al.*, 2008; *Rockström et al.*, 2009; *Wisser et al*., 2010; *Wada et al.*, 2011b; *Wada et al.*, 2014].

Water availability is highly variable over space and time, and water stress may occur when several water demand sectors compete for the same scarce water resources. To evaluate the deficiency of water resources, *Falkenmark* [1989] introduced the water scarcity index (WSI) that analyses the ratio of water demand to water availability. Water stress emerges in a river basin when water availability falls below 1700 $m^3\ yr^{-1}$ per capita, becomes severe when water availability is under 1000 $m^3\ yr^{-1}$ per capita, and is characterized as extreme when the water supply drops below 500 $m^3\ yr^{-1}$ per capita [*Falkenmark et al*., 2007; *Kundzewicz et al*., 2007]. *Wada et al*. [2011b] estimated that ~ 800 million people were suffering of water scarcity in 1960. Contemporary global estimates of population living under water-stressed conditions range from 1.2 to 2.4 billion [*Vörösmarty et al*., 2000; *Alcamo et al*., 2000; *Oki et al*., 2001; *Arnell et al*., 2004; *Alcamo et al*., 2007; *Islam et al*., 2007; *Hanasaki et al*., 2008a,b; *Kummu et al*., 2010; *Wada et al*., 2011b]. *Alcamo et al*. [2007] reported increasing irrigation water withdrawals as one of the main causes of future water stress.

Improving irrigation water efficiencies would benefit to green water flows sustainability, secure the provisioning of terrestrial ecosystem functioning and services, make sufficient blue water available for aquatic ecosystems, and mitigate the competition between water demand sectors.

2. Scientific question and research objectives

With growing global population and living standards, irrigation water supply to cultivated crops becomes increasingly essential to sustain food production, yet remains the most important sector of human water use and the main cause of the intense competition between users in the context of globalization and global water scarcity. In these circumstances, it is crucial that the efficiency of irrigation water use is improved to reduce water losses during conveyance, distribution and application of water. The objective of irrigation water efficiencies improvement is to reduce water demand, attain higher crop yields, and ultimately alleviate the pressure of irrigation activities on natural water resources and the ecosystem.

Hydrological modeling studies have helped evaluating the type and the magnitude of irrigation activities effects on water resources. Irrigation efficiency improvements are urgently needed to avoid or reduce competition for water resources, lower the risk of water scarcity, and enable sustainable water productivity for food security.

The main research question is to evaluate, for a limited number of river basins, how improvements in irrigation efficiency interact with changes in irrigated area, how these improvements alter total irrigation water demand in relation to variations and trends in water availability for these regions and how these developments translate to global changes in water availability and water demand.

This study aims to evaluate the developments of irrigation efficiency at the river basin scale in the perspective of increasing food demand over the past (i.e., 1960-2010) and over the future (i.e., 2010-2099). This assessment is performed over catchments of varying levels of irrigation technology and infrastructural development in order to understand the mechanisms of change in global water availability due to improving irrigation efficiency. Global food security remains at risk due to climate change and increasing water scarcity. This study provides an assessment of the evolution of water availability for irrigation in relation to improving irrigation efficiency in the context of increasing competition for water resources and water scarcity. To achieve this, water availability is simulated and contrasted against crop water requirements, including irrigation water efficiencies in the computation of irrigation water demand, in order to assess the degree of irrigation requirements satisfaction and the evolution of water resources availability.

Objectives of the study are:

- Evaluate trends in irrigation efficiency;
- Evaluate potential irrigation efficiency improvements over existing irrigated areas;
- Include allocation of surface water and groundwater contribution to irrigation water supply;
- Account for the uncertainty arising from irrigated areas, cropping patterns and cropping calendars data sets;
- Account for the uncertainty arising from the variability and trends in climate forcing;
- Account for climate change trends effect on water resources availability.

Contemporary and future developments of irrigation efficiency are compared to trends in climate variability for the present and future climate conditions in order to differentiate their implication for water productivity. Present and future climate conditions are represented using the CRU TS 3.21 monthly data set [*Harris et al*., 2013] and three global climate model (GCM) projections. Changes in water availability are evaluated in detail in four selected major river basins subject to irrigation with contrasting technological development and type of water source (i.e., groundwater, surface water): the Indus (i.e., traditional, low efficiency irrigation), Mekong (low efficiency, monsoon-dependent paddy irrigation), Yellow River (developing, moderately effective irrigation), and Mississippi (highly efficient non-paddy irrigation) river basins.

3. Previous work on the problem

3.1 Historical development

Hydrology emerged during the 19th century and proved to be a useful and necessary science. However, hydrology lagged until the half of the 20th century as hydrologists did not make full use of new methods in science [*Nace*, 1965]. The recognition of hydrology as a crucial science only came in the fifth and sixth decades with the awareness of the social and environmental impacts of river management projects and concerns about food security. In 1949, irrigation and water supply were two of the major topics discussed, based on international experiences, at the Lake Success Conference on the Conservation and Utilization of Resources (*United Nations*, 1951). Globally, an increasing number of regional assessments of water availability and water demand were performed along with the international hydrological decade (1965–1974) (*UNESCO*, 1966) which promoted studies on water and led to the establishment of the International Hydrological Program (*White*, 1998).

In the late sixties and seventies, the connection between irrigation water use and agricultural productivity started to draw the attention of hydrologists and water management entities. *De Wit* [1968] and *Kassam* [1977] developed two different procedures for estimating maximum crop yields on which is based the original FAO's equation on the relationship between crop yield and irrigation water use, published in the *FAO Irrigation and Drainage Paper No. 33* [*Doorenbos and Kassam*, 1979; *FAO*; 2012].

In the next decades, it became clear with results of hydrological modeling studies that water resources and natural hydrological processes were increasingly affected by human activities, in particular by water abstractions for irrigation purposes (e.g., *Vörösmarty et al*. [2000], *Oki et al*. [2001], *Alcamo* [2003], *Döll and Siebert* [2002]). As concerns emerged about food security and the globally increasing water scarcity issue, efforts to assess water availability, water demand, global and regional water stress, and crop water requirements with macro-scale hydrological models (MHMs) and global-scale hydrological models (GHMs) have increased over the last decades [*Smakhtin et al*., 2004]. An overview of hydrological models used in previous studies to compute water balance, water stress, irrigation water requirements and irrigation water consumption over the past, the present, and the future, is shown in Table 2.1.

The TRIP (Total Runoff Integrating Pathways), WaterGAP 1.0 (Water-Global Assessment and Prognosis), Macro-PDM, and WBM (Water Balance Model) models were among the first models applied to simulate global surface water balance and surface water availability at a spatial resolution of 0.5° or 30 arc min (about 50 km at the equator) [*Oki and Sud*, 1997; *Alcamo et al*., 1997; *Arnell*, 1999; *Vörösmarty et al*., 2000; *Oki et al*., 2001]. In addition to the simulation of global surface water availability, the WGHM model (0.5°), a submodel of the global hydrological model WaterGAP 2, was among the first models that account for the reduction of river flow caused by industrial, domestic and agricultural water use [*Alcamo et al*., 2003a, b; *Döll et al*., 2003]. Further, the H08 model (0.5°) was developed to include irrigation withdrawals and reservoir regulation operations in the global surface water balance calculation [*Hanasaki et al*., 2008a, b, 2010]. The WBM_{plus} (0.5°) and PCR-GLOBWB (0.5°) models were developed to incorporate reservoirs operations and sectoral water demand affecting the water cycle processes, including groundwater resources, in the computation of global surface water balance at a sub-annual temporal resolution (i.e. monthly time step) [*Wisser et al*., 2010; *Wada et al*., 2010, 2011a, b; *Van Beek et al*., 2011]. The PCR-GLOBWB global hydrological model was further improved with a new water demand and irrigation module, a dynamic scheme to represent abstractions, allocation, and consumptive use of surface water and groundwater resources, an improved routing scheme able to simulate flooding, and a new dynamic attribution scheme of water demand to surface water and groundwater resources that accounts for the actual availability of water resources, explicitly including the effects of return flows on surface water and groundwater systems and the interactions between surface water bodies and the groundwater resources [*Wada et al*., 2012a; *Winsemius et al*., 2013; *Wada et al*., 2014; *De Graaf et al*., 2014; *Sutanudjaja et al*., 2014].

While our land and water resources are clearly limited, human water and food demand continue to increase. In this context, and especially in the case of irrigation water use, previous hydrological modeling studies have provided valuable information for sustainable and optimal water use. These studies have demonstrated the necessity of pursuing modeling efforts to increase our capacity to cope with climate change and human impacts on the water resources and natural hydrological processes [*Smith*, 1992; *Allen et al*., 1998; *Rockström and Falkenmark*, 2000; *FAO*, 2002, 2012; *Smakhtin et al*., 2004; *Rohwer et al*., 2007; *Rost et al*., 2008; *Siebert and Döll*, 2010; *Wisser et al*., 2010; *Montague-Fuller*, 2014].

3.2 Hydrological Models

Macro-scale hydrological models (MHMs) and global-scale hydrological models (GHMs) were developed to simulate water balance at the river basin scale and at the global scale, respectively. These models are aimed at reproducing land surface hydrological dynamics. The development of models that reproduce hydrological processes at the local, regional and global scales improved the scientific knowledge on the hydrological cycle, the type and magnitude of climate change and human activities effects on water resources, and allowed a better understanding of the intricacies related to water management and water use. For instance, recently made available global water demand data sets have been used as model input in hydrological modeling studies and have allowed the computation of water stress at the global scale (e.g., *Van Beek et al*. [2011], *Wada et al*. [2011a]).

Land surface models (LSMs) were primarily designed to represent land-atmosphere water interactions, hence to carry out climate simulations in global climate models (GCMs) (e.g., NOAH [*Ek et al*., 2003]). Dynamic vegetation models (DVMs) were developed to assess vegetation-climate hydrological interactions in the context of climate change and under the influence of anthropogenic activities on water resources (e.g., LPJmL [*Rost et al*., 2008; *Konzmann et al*., 2013]). LSMs do not account for the anthropogenic activities impact while DVMs include human-induced CO_2 increase and human activities effects such as irrigation water use impact on water resources. MHMs and GHMs comprise the impact of all types of human activities on the hydrological cycle (i.e., reservoir regulations, agricultural, industrial, and domestic water withdrawal and consumption). Coupling GHMs with GCMs allows for appropriate future projections of water availability and water demand, and the inclusion of climate change impact on the amount of available water resources. The main characteristics of hydrological models applied in previous studies are discussed in Section 2.2.1, and the inclusion of irrigation schemes in these models is reviewed in Section 2.2.2.

3.2.1 Main characteristics

During the first decade of the 21st century, numerous studies have used MHMs and GHMs to provide assessments of water availability, water demand and water stress (e.g., *Vörösmarty et al*. [2000], *Oki et al*. [2001], *Arnell* [1999, 2004], *Alcamo* [2003, 2007], *Widén-Nilsson et al*. [2007, 2009]) at a spatial resolution of 0.5°, making use of recently developed hydrological and climatic data available at a grid-cell resolution of 30 arc min (about 50 km at the equator). Several studies have included GCM runs in their simulation process in order to estimate future water availability and future developments of water stress using human population projections, while including climate variability and climate change effects on future water resources (e.g., *Vörösmarty et al*. [2000], *Arnell* [1999, 2004], *Alcamo et al*. [2007, 2010]). Most of the major rivers in the world are regulated by large artificial reservoirs (i.e., with a storage capacity ≥ 0.5 km^3). Therefore, most recent studies include reservoir and lake operation schemes using global repositories (e.g., the Global Lake and Wetland database GLWD [*Lehner and Döll*, 2004] and the Global Reservoir and Dam database GRanD [*Lehner et al*., 2011]) and release objective rules in order to represent the effects of altered seasonal river flow on water availability, especially in the case of water storage for drier periods with higher water demand [*Vörösmarty et al*., 2000, 2004; *Alcamo*, 2003; *Nilsson et al*., 2005; *Haddeland et al.*, 2006; *Hanasaki et al*., 2006, 2008a, b, 2010, *Widén-Nilsson et al*., 2007, 2009; *Rost et al*., 2008, 2009; *Wisser et al.*, 2008, 2010; *Alcamo et al.*, 2010; *Hanasaki et al.*, 2010; *Biemans et al*., 2011, 2013; *Van Beek et al.*, 2011, *Sutanudjaja et al*., 2014]. In addition, the recent development of water demand data sets has led to a significant increase in the inclusion of water withdrawal and water consumption for irrigation, domestic, and industrial purposes in the simulation of hydrological processes [*Alcamo*, 2000, 2003; *Oki et al*., 2001; *Arnell*, 2004; *Hanasaki et al*., 2006, 2008a, b, 2010; *Alcamo et al*., 2007, 2010; *Rost et al*., 2008, 2009; *Wisser et al.*, 2010; *Van Beek et al.*, 2011; *Wada et al*., 2011a; *Wada et al*., 2014]. Recently developed hydrological models run at the spatial resolution of 5 arc min (about 10 km at the equator), hence supersede the generation of models running at 30 arc min (0.5°) spatial resolution, while their development will continue to include more comprehensive and dynamic modules to improve the simulation of natural and human-disturbed hydrological processes [*Sutanudjaja et al*., 2014]. Further, new hydrological intercomparison projects and multimodel studies enable a cross-sectoral and cross-scale (i.e. at different spatial and temporal scales) approach of the water cycle, allowing a better understanding of human activities and climate change impacts on natural hydrological processes and water resources [*Wada et al*., 2013c; *Warszawski et al*., 2014].

Table 3-1: Main characteristics of existing, current hydrological models used to assess the human impact on the hydrological cycle.

Previous studies	Main focus	Model (spatial resolution)	Time step	Study period	Climate input	Reference Evapotranspiration	Reservoir/River routing scheme	Soil[1]	Irrigated area	Crop	Crop calendar	Climate change	Additional components
Arnell [1999, 2003]	Global water balance, emission scenarios effects on river runoff	Macro-PDM (0.5°)	Month	1961-1990	CRU[2] [New et al., 1999]	Penman, Penman-Monteith, Priestley and Taylor	-	FAO	-	-	-	HadCM3[3], CSIRO[4], CGCM2[5], ECHAM4[6], GFDL-R30[7], CCSR/NIES2[8]	IPCC SRES[9] emission scenarios
Alcamo [2000, 2003]	Global water use and availability	Water-Global Assessment and Prognosis (WaterGAP2) (0.5°)	Day	1961-1990	CRU TS 1.0 [New et al., 2000]	Priestley and Taylor [Döll and Siebert, 2002]	Bergström [1994], Global Drainage Direction map (DDM30) [Döll and Lehner, 2002]	Batjes [1996]	Döll and Siebert [2000]	Rice/ other crops	Optimal growth	-	
Vörösmarty et al. [2000]	Contemporary and future water availability and water stress	Water Balance Model (WBM) (0.5°)	Day	1985-2025	-	Fekete et al. [1999]	Digitized rivers [Vörösmarty et al., 1998; Fekete et al., 1999]	-	Döll and Siebert [1999]	No distinction between crop types	-	CGCMI[10], HadCM2[12]	Scenarios represent a 1% per year increase in $C0_2$ equivalent forcing and sulfate aerosol dampening
Oki et al. [2001]	Water availability and water demand	Total Runoff Integrating Pathways (TRIP) (0.5°)	10 days	1987-1988	ISLSCP[13] [Meeson et al., 1995]	-	Total Runoff Integrating Pathways (TRIP) [Oki et al., 1997; Oki and Sud, 1998]	-	Döll and Siebert [2000], SAGE[14]	-	-	-	Population under water scarcity
Döll and Siebert [2002]	Irrigation water requirements	Water-Global Assessment and Prognosis (WaterGAP) (0.5°)	Day	1961-1990	CRU TS 1.0 [New et al., 2000]	Priestley and Taylor	-	FAO	Döll and Siebert [2000]	Paddy/ non-paddy	Optimal growth	-	Net/gross irrigation water consumption
Arnell [2004]	Population under water scarcity	Macro-PDM (0.5°)	Month	1961-2099	CRU [New et al., 1999]	-	-	-	-	-	-	HadCM3, CSIRO-Mk2[16], CGCM2, ECHAM4-OPYC[17], GFDL-R30, CCSR/NIES2	IPCC SRES emission scenarios
Haddeland et al. [2006]	Reservoirs and irrigation water withdrawals	Variable Infiltration Capacity (VIC) (0.5°) [Liang et al., 1994]	Day	1980-1999	Adam et al. [2006], Maurer et al. [2002]	FAO Penman-Monteith	Vrugt et al. [2003], ICOLD[18] [1998]/Lohmann et al. [1998], Maurer et al. [2002], Simulated Topological Networks (STN-30p)[Vörösmarty et al. 2000b]	-	Siebert et al. [2002]	Haddeland et al. [2006]	Optimal growth	-	Consumptive irrigation water use, objective functions to determine reservoir releases
Hanasaki et al. [2006]	Reservoir operation effects on global hydrology	Total Runoff Integrating Pathways (TRIP) (Oki et al., 2001) (1.0°)	10 days	1987-1988	ISLSCP[19] [Meeson et al., 1995]	FAO Penman-Monteith	Total Runoff Integrating Pathways (TRIP) [Oki et al., 1997; Oki and Sud, 1998]	GSWP[20] [Dirmeyer et al., 1999]	Döll and Siebert [2000]	Paddy/ non-paddy	Optimal growth	-	Irrigation water supply from reservoirs
Alcamo et al. [2007]	Future water availability and water stress	Water-Global Assessment and Prognosis (WaterGAP2) (0.5°)	Day	1961-2070	CRU TS 1.0 [New et al., 2000]	Priestley and Taylor	Lake and wetland scheme [Döll et al., 2003], Global Drainage Direction map (DDM30) [Döll and Lehner, 2002]	FAO	Döll and Siebert [2000]	Paddy/ non-paddy	Optimal growth	ECHAM4/OPYC3[21], HadCM3	A2, B2 IPCC SRES emission scenarios
Widén-Nilsson et al. [2007, 2009]	Global water balance	Water and Snow Balance Modeling System (WASMOD-M) (0.5°)	Month	1915-2000	CRU TS 2.02 [Mitchell et al., 2004]	Xu [2002]	Simulated Topological Networks (STN-30p) [Vörösmarty et al. 2000a, b]	-	-	-	-	-	
Hanasaki et al. [2008a,b]	Global water resources	H08 (1.0°)	Day	1986-1995	F-GSWP2-B1 [Hanasaki et al., 2008a]	Bukl formula [Robock et al., 1995]	Reservoir routing scheme [Hanasaki et al., 2006]	FAO	Döll and Siebert [2000]	Primary/secondary crop types [Leff et al., 2004]	Soil moisture maintained at 75% of field capacity in irrigated fields	-	Total consumptive water withdrawal, irrigation water use

Table 2.1 (continued): Main characteristics of existing, current hydrological models used to assess the human impact on the hydrological cycle.

Rost et al. [2008, 2009]	Agricultural water consumption under current and future climate	Lund-Postdam-Jena managed Land (LPJmL) (0.5°) [Bondeau et al., 2007]	Day	1901-2070	CRU TS 2.1 [Mitchell and Jones, 2005]	Priestley and Taylor [Gerten et al., 2007]	Global Lakes and Wetlands Database (GLWD) [Lehner and Döll, 2004], Global Drainage Direction map (DDM30) [Döll and Lehner, 2002]	FAO	Evans [1997], Ramankutty and Foley [1999], Siebert et al. [2007]	12 crops/ pasture	Vegetation/crop growth simulated by LPJmL [Bondeau et al., 2007], optimal growth	HadCM3, ECHAM5/MPI-OM[22], CCSM3	Green and blue water consumption, crop production
Wisser et al. [2008, 2010]	Global water balance and agricultural water demand over the 20th century	Water Balance Model plus (WBMplus) (0.5°)	Day	1901-2002	CRU TS 2.1 [Mitchell and Jones, 2005], NCEP/NCAR [Kalnay et al., 1996]	Hamon	Large and small reservoirs routing scheme [Wisser et al., 2010]/Framework for Aquatic Modeling in the Earth System (FrAMES) [Wollheim et al., 2008]	FAO	Siebert et al. [2005, 2007] Thenkabail et al. [2006]	Monfreda et al. [2008]	Optimal growth	-	Trends in hydrological components
Alcamo et al. [2010]	Contemporary and future water availability and water withdrawals	Water-Global Assessment and Prognosis (WaterGAP2) (0.5°)	Day	1961-2025	CRU TS 1.0 [New et al., 2000]	Priestley and Taylor	Bergström [1994] Global Drainage Direction map (DDM30) [Döll and Lehner, 2002]	FAO	Döll and Siebert [2000]	Paddy/ non-paddy	Optimal growth	Business-As-Usual (BAU) scenario	Change in irrigated area
Hanasaki et al. [2010]	Global agricultural water withdrawal	H08 (0.5°)	Day	1985-1999	NCC-NCEP/NCAR[23] renalysis CRU TS 1.0 [New et al., 1999] corrected [Ngo-Duc et al., 1995, 2005]	Bukl formula [Robock et al., 1995]	Reservoir routing scheme [Hanasaki et al., 2006], ICOLD [1998]	-	Siebert et al. [2005]	Monfreda et al. [2008]	Cropping calendar simulated by H08 [Hanasaki et al., 2008b]	-	Global virtual water export
Siebert and Döll [2010]	Agricultural blue and green consumptive water use	Global Crop Water Model (GCWM) (0,083333°)	Day	1998-2002	CRU TS 2.1 [Mitchell and Jones, 2005]	FAO Penman-Monteith, Priestley and Taylor	-	Batjes [2006]	Portmann et al. [2008, 2010]	26 crops [Portmann et al., 2010]	Portmann et al. [2010]	-	Irrigated and rainfed crop yield
Van Beek et al. [2011] Wada et al. [2011]	Global water stress	PCRaster Global Water Balance (PCRGLOBWB) (0.5°)	Day	1958-2001	CRU TS 2.1 [Mitchell and Jones, 2005]	FAO Penman-Monteith	Reservoir routing scheme [Van Beek et al., 2011], Exogeneous runoff scheme	FAO	Portmann et al. [2010]	26 crops [Portmann et al., 2010]	Portmann et al. [2010] Siebert and Döll [2010]	-	Sectoral water demand
Wada et al. [2013]	Trends in future irrigation water demand	H08, LPJmL, MPI-HM[24], PCR-GLOBWB, WaterGAP, WBMplus, VIC (all 0.5°)	Day	1971-2099	-	-	-	FAO, LSP2[24], GSDP[25]	Siebert et al. [2007], Fader et al. [2010], Portmann et al. [2010]	-	-	HadGEM2-ES[26], IPSL-CM5A-LR[27], MIROC-ESM-CHEM[28], GFDL-ESM2M[29], NorESM1-M[30]	GHMs and climate projections uncertainties
De Graaf et al. [2014]	allocation of surface water and groundwater contribution to human activities	PCRaster Global Water Balance (PCRGLOBWB) (0.5°)	Day	1960-2010	CRU TS 2.1 [Mitchell and Jones, 2005], ERA-40 reanalysis [Uppala et al., 2005]	FAO Penman-Monteith	Global Lakes and Wetlands Database 1 (GLWD1) [Lehner and Döll, 2004], Global Drainage Direction map (DDM30) [Döll and Lehner, 2002]	FAO	Portmann et al. [2010]	26 crops [Portmann et al., 2010]	Portmann et al. [2010] Siebert and Döll [2010]	-	Feedbacks between surface water and groundwater and their exploitation
Wada et al. [2014]	Global surface water and groundwater use	PCRaster Global Water Balance (PCRGLOBWB) (0.5°)	Day	1979-2010	CRU TS 2.1 [Mitchell and Jones, 2005], ERA-Interim reanalysis [Dee et al., 2011], MERRA reanalysis [Rienecker et al., 2011]	FAO Penman-Monteith	Global Reservoir and Dams data set (GRanD) [Lehner et al., 2011]/Simulated Topological Networks (STN-30p) [Vörösmarty et al. 2000a, b]	FAO	Portmann et al. [2010]	Paddy/ non-paddy	Portmann et al. [2010]	-	Withdrawal and consumption of surface water and groundwater, feedback between availability and demand

[1] FAO: FAO Digital Soil Map of the World; http://www.fao.org/nr/land/soils/digital-soil-map-of-the-world

[2] CRU: Climate Research Unit

[3] Met Office Hadley Centre; *Gordon et al.*, 2000; *Pope et al.*, 2000

[4] *Hirst et al.*, 1996
[5] Coupled Global Climate Model; *Flato and Boer*, 2001
[6] *Roeckner, et al.*, 1992
[7] *Delworth et al.*, 2002; *Dixon et al.*, 2003
[8] *Abe-Ouchi et al.*, 1996
[9] Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios
[10] Canadian (Centre) General Circulation Model 1; *Flato et al.*, 2000
[11] *Cullen*, 1993
[12] International Satellite Land Surface Climatology Project
[13] Center for Sustainability and the Global Environment, University of Wisconsin-Madison, USA
[14] *Gordon and O'Farrell*, 1997; Hirst *et al.*, 1999
[15] *Bacher et al.*, 1998
[16] International Commission on Large Dams
[17] Global Soil Wetness Project
[18] Max Planck Institute of Climatology, Germany, German Climate Computing Center (Deutsches Klimarechenzentrum); *Roeckner et al.*, 1996; *Cubasch et al.*, 2001
[19] *Roeckner et al.*, 2003; *Marsland et al.*, 2004
[20] National Centers for Environmental Prediction/National Center for Atmospheric Research; *Kistler et al.*, 2001
[21] *Stacke and Hagemann*, 2012; *Hagemann and Gates*, 2013
[22] Global Dataset of Land Surface Parameters; *Hagemann*, 2002
[23] Global Soil Data Products (IGBP-DIS: International Geosphere-Biosphere Programme Data and Information System); http://daac.ornl.gov/SOILS/igbp.html
[24] *Jones et al.*, 2011
[25] *Mignot and Bony*, 2013; *Dufresne et al.*, 2013
[26] *Watanabe et al.*, 2011
[27] *John et al.*, 2013
[28] *Bentsen et al.*, 2012, 2013

3.2.2 Inclusion of irrigation scheme

Climate data (e.g., rainfall, temperature, reference evapotranspiration) is used to force hydrological models in order to simulate the actual evapotranspiration that occurs over irrigated areas (i.e., the amount of green water available to cultivated crops). The difference between crop-specific potential evapotranspiration and available soil moisture is computed over irrigated areas. It represents the net irrigation water requirements that must be applied to the soil so that maximum potential evapotranspiration is achievable, hence optimal crop productivity. To ensure that crop evapotranspiration occurs at the maximum potential rate, more water than the net crop water requirements needs to be withdrawn, transported and applied to the field. This additional amount depends on the type of crop and on the overall or project efficiency. Hydrological models are used to compute this volume of water, referred to as gross irrigation water requirements.

Döll and Siebert [2002] carried out one of the first global assessments of irrigation crop water requirements at a spatial resolution of 0.5° longitude by 0.5° latitude, using an improved version of the WaterGAP 1.0 model [*Alcamo et al*., 1997]. The objective of this study being the identification of water scarcity at the global scale, *Döll and Siebert* [2002] did not simulate the actual irrigation water use, but rather modeled irrigation water requirements that lead to optimal crop growth. Furthermore, little data on irrigated areas and irrigated crops was available, with the exception of rice. Hence, the model was restricted the calculation of the net and gross irrigation water requirements for rice and non-rice crops: net irrigation water requirements were computed as the difference between the potential evapotranspiration and the evapotranspiration that would occur without irrigation, while gross irrigation water requirements were calculated by taking into account losses related to the irrigation technology and field management.

Most recent studies include irrigation water demand to better estimate water availability, total water demand and water stress (e.g., *Haddeland et al*. [2006a, b], *Hanasaki et al*. [2006, 2008a, b, 2010], *Wisser et al*. [2008, 2010], *Wada et al*. [2011b]). *Haddeland et al*. [2006a, b] used the VIC (Variable Infiltration Capacity) macroscale hydrology model [*Liang et al*., 1994] to simulate the water balance over selected irrigated regions (e.g., North America) and study the impact of human activities on hydrological processes, while focusing on irrigation and reservoir operations. In *Haddeland et al*.'s [2006a] irrigation scheme, irrigation is scheduled to start when soil moisture reaches a lower threshold, corresponding to the moment when transpiration becomes limited, and stops when the green water availability reaches field capacity. Both rainfed and irrigated areas are included in the VIC model with the global map of irrigated areas from *Siebert et al*. [2002]. The irrigation scheme developed by *Haddeland et al*. [2006a] pioneered the use of attribution rules of irrigation water abstraction to surface water or reservoirs. Further, the VIC model can take into account water availability in specific cases so that irrigation water abstractions can be restricted. However, groundwater abstractions were not implemented in the VIC model due to a poor representation of groundwater flow processes [*Haddeland et al*., 2006b].

Wada et al. [2010] used the global hydrological model PCR-GLOBWB [*Van Beek and Bierkens*, 2009] to solve the global water balance, evaluate groundwater availability and groundwater recharge, and estimate global groundwater abstraction at a spatial resolution of 0.5°. The objective of this study was to identify groundwater depletion areas and evaluate the magnitude of groundwater supply to irrigation. Due to the deficiency of information on groundwater abstraction for most of the countries, *Wada et* al. [2010] had to downscale groundwater withdrawal per country, assuming that groundwater is abstracted in the areas where it is required.

Expending on this study, *Wada et al*. [2012a] used the PCR-GLOBWB model to estimate the volume of blue water required to satisfy gross irrigation water demand, and to quantify the global volume of non-renewable groundwater abstracted for irrigation purposes for the year 2000. Non-renewable groundwater corresponds to groundwater withdrawn in excess of the groundwater recharge rate for any region of the world [*Vörösmarty et al.*, 2005]. In this study, water demand was restricted to irrigation. Net irrigation water demand was computed by assuming optimal crop growth. Gross irrigation water demand was computed by including the evaporative and percolation losses that occur during conveyance and application of irrigation water. *Wada et al*. [2012a] used data on major aquifers from the IGRAC (International Groundwater Resources Assessment Centre) GGIS database to compute the deficits between surface water availability and net irrigation water requirements. Assuming that any remaining irrigation water demand (i.e., the calculated deficits) is met from groundwater resources, groundwater abstractions were subsequently divided into a renewable and a non-renewable fraction by taking into account the simulated natural groundwater recharge and the additional recharge from irrigation.

Over the last decades, hydrological models have been applied in order to evaluate the volumes of water abstracted and consumed for irrigation purposes (Section 2.3). The estimation of the volumes of water abstracted and consumed by irrigation activities was further detailed by considering the actual, limited availability of surface water and groundwater resources for irrigation (Section 2.4). Modeling improvements and the results of previous hydrological studies have provided new methods to account for the effects of irrigation activities on the water cycle in the past and in the present, and to evaluate the current state of global water resources (Section 2.5) In the same way, the impact of irrigation activities on future water resources was also assessed by simulating future hydrological processes with hydrological models coupled with GCMs (e.g., *Döll and Siebert* [2002], *Rost et al*. [2008, 2009], *Wada et al*. [2013c]).

Information on the areas under irrigation and on the types of crops cultivated over these areas is prerequisite to comprehensively evaluate the impact of irrigation activities on global water resources. To that end, irrigated areas data sets have increasingly been developed since the last decade of the 20^{th} century. Examples are the FAO/University of Frankfurt Global Map of Irrigated Areas (GMIA) [*Siebert et al.*, 2000, 2002, 2005, 2007], the Global Irrigated Area Map (GIAM) from the International Water Management Institute (IWMI) [*Thenkabail et al*., 2006], and the global data set of monthly irrigated and rainfed crop areas around the year 2000 (MIRCA2000) [*Portmann et al*., 2010]. Information on irrigated areas is discussed in the Section 4.3.2.

3.3 Irrigation water requirements and irrigation water consumption

Over the last decade, hydrological models have become more accurate at simulating natural hydrological processes. The human impact on global water resources is the core of hydrological scientific interest. Differentiating between irrigation water requirements and consumption is critical to evaluate the actual changes in water resources availability and in the exploitation intensity thereof. Information on the trends of irrigation water use is crucial to provide guidance for a better irrigation water management, avoid or alleviate competition between water users, while enabling a sustainable water productivity and food security.

Prerequisites to estimate irrigation water requirements are information on the extent of irrigated areas, the cropping patterns, cropping calendars, cropping intensity, the type of cultivated crops, crop-related variables (e.g., crop coefficients, effective rooting depth), and the climate conditions (e.g., surface air temperature, rainfall rates).

Irrigated crops evapotranspiration is calculated by using crop coefficients multiplied by the reference evapotranspiration. The crop coefficient method [*Allen et al*., 1998] is widely used and has been applied in numerous studies to compute crop evapotranspiration and irrigation water requirements (e.g., *Döll and Siebert* [2002], *Wisser et al*. [2008], *Siebert and Döll* [2010], *Wada et al.* [2011b], *Wada et al*. [2014]). Irrigation crop water requirements are calculated by hydrological models and compared to the actual transpiration. The difference corresponds to net irrigation water requirements. This volume represents the amount of water that has to be supplied in addition to the green water in order to enable potential crop evapotranspiration, hence optimal crop growth and maximum crop productivity.

Gross irrigation water requirements are subsequently computed by taking into account the efficiency of irrigation technology and water management, that is, by including the losses that occur during irrigation water abstraction, transport, storage, distribution, and application to the field. The magnitude of losses depends on the type of irrigation technology at the disposal of the user, and the quality of the water supply infrastructures.

The figure 2.1 shows prior assessments of irrigation water requirements and consumption.

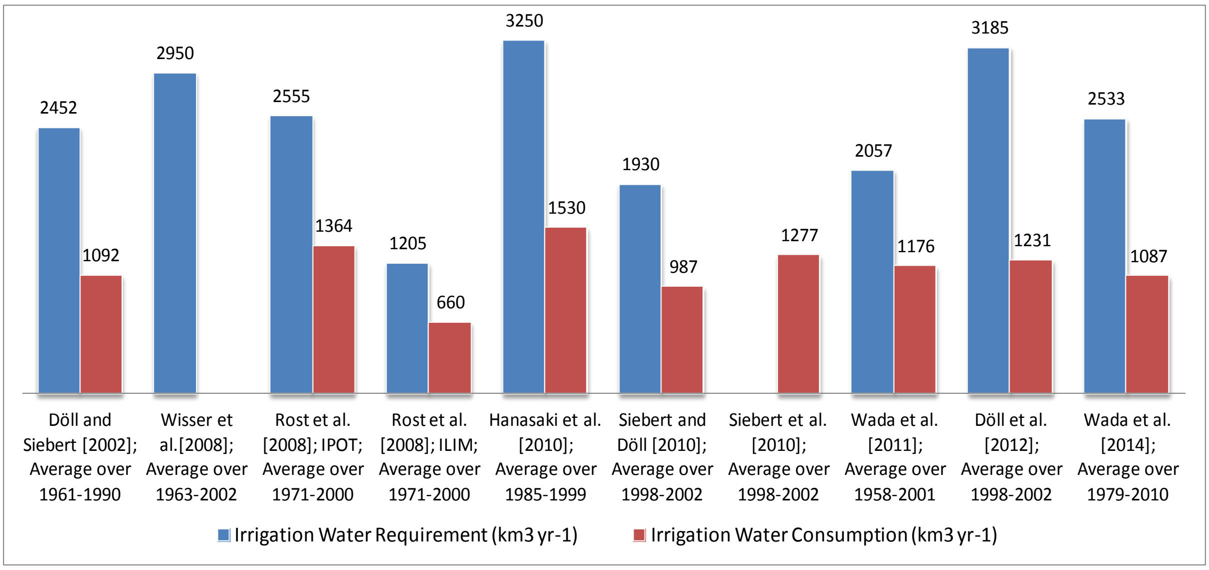

Figure 3-1: Previous studies to estimate irrigation water requirements and consumption.

Döll and Siebert [2002] used the WaterGAP 1.0 model [*Alcamo et al*., 1997] to simulate rice and non-rice crops net and gross irrigation water requirements over the area equipped for irrigation in 1995 reported in the Global Map of Irrigated Areas (GMIA) [*Döll and Siebert*, 2000], assuming optimal crop growth. Net and gross irrigation water requirements are computed over the period 1961-1990 due to the unavailability of long-term average sunshine values before this period. The estimated global net irrigation crop water requirements are 1092 km^3 yr^{-1}, and the estimated gross irrigation water requirements are 2452 km^3 yr^{-1}.

Wisser et al. [2008] simulated irrigation water withdrawals (i.e., gross irrigation requirements) over irrigated areas around the year 2000 for the period 1963-2002, using the WBM_{plus} model. The FAO/University of Frankfurt Global Map of Irrigated Areas (GMIA) [*Siebert et al*., 2005, 2007] and the Global Irrigated Area Map (GIAM) from the International Water Management Institute (IWMI) [*Thenkabail et al*., 2006] were used to represent the extent of irrigated areas around the year 2000. Additionally, *Wisser et al*. [2008] used two climate data sets in order to retrieve climate drivers (i.e., daily air temperature, precipitation) for the period 1963-2002, and to account for climate variability and uncertainty: the CRU TS 2.1 global monthly climate data set [*Mitchell and Jones*, 2005] and the global daily NCEP/NCAR reanalysis product [*Kalnay et al*., 1996]. Using irrigated areas information from the GMIA with CRU TS 2.1 data, estimated irrigation water withdrawals amount to 3100 km^3 yr^{-1}. When the model includes irrigated areas from the GIAM, irrigation water requirements are 3800 km^3 yr^{-1}. The combination of the NCEP/NCAR climate data with both irrigated data sets results in estimated irrigation water withdrawal volumes of 2200 km^3 yr^{-1} (GMIA) and 2700 km^3 yr^{-1} (GIAM). By taking the average of the different simulations, *Wisser et al*. [2008] estimate that gross irrigation water requirements are 2950 km^3 yr^{-1} over the period 1963-2002.

However, in some cases (e.g., water scarcity), it is not possible to irrigate optimally, hence to satisfy optimal crop growth. Therefore, ctual irrigation water requirements and consumption are lower than the gross and net irrigation water requirements.

In *Rost et al*. [2008] study, the LPJmL model [*Bondeau et al*., 2007] is used to compute two estimates of irrigation water requirements over the period 1971-2000, by considering two water availability scenarios. In the potential irrigation simulation (IPOT), gross irrigation water requirements are supplied to the crops in order to satisfy potential crop evapotranspiration, assuming that water availability is always guaranteed, and that crops do not experience water stress. This simulation hence implicitly considers irrigation water supply from non-renewable fossil groundwater and non-local water sources. Inversely, in the limited irrigation simulation (ILIM), *Rost et al*. [2008] impose restrictions on irrigation water supply: water availability in each grid cell is restricted to the volume of water stored in rivers, lakes and reservoirs. Fossil groundwater (i.e., non-renewable groundwater), desalinated water, transported and diverted (i.e., non-local) water are not explicitly included in the LPJmL model due to the deficiency of information on groundwater resources, and because diversions are not included in the prescribed routing scheme. In the IPOT simulation, irrigation water withdrawals range from 2534 to 2566 km^3 yr^{-1} (average is 2555 km^3 yr^{-1}) while in the ILIM simulation, the irrigation water requirements range from 1161 to 1249 km^3 yr^{-1} (average is 1205 km^3 yr^{-1}). In the IPOT simulation, the irrigation water consumption is comprised between 1353 and 1375 km^3 yr^{-1} (average is 1364 km^3 yr^{-1}). In the ILIM simulation, irrigation water consumption ranges from 636 to 684 km^3 yr^{-1} (average is 660 km^3 yr^{-1}). Figure 2.1 only displays the average values. The ranges of simulation values stem from the use of different precipitation inputs.

In the same way than in the IPOT simulation of *Rost et al*. [2008], *Hanasaki et al*. [2010] consider non-renewable and non-local sources of water with green water resources in the model H08 to compute irrigation water requirements over the period 1985-1999. In this study, water availability from deep groundwater, lakes, glaciers, water diverted, and desalination is assumed limitless, due to the lack of data on the capacity of each source. In the H08 model, irrigation water is withdrawn first from rivers, while the environmental flow requirement is always left in the channel. If irrigation water requirements are not satisfied by the volume of water abstracted from rivers, water is withdrawn from medium-sized reservoirs, if any, and when these reservoirs are depleted, water is assumed supplied from non-renewable and non-local water resources. Irrigation water requirements are computed over irrigated areas from *Siebert et al*. [2005], using crop data from *Monfreda et al.* [2008] and *Ramankutty et al*. [2008]. *Hanasaki et al*. [2010] estimate that irrigation water withdrawal and consumption volumes (referred to as total evapotranspiration from irrigated cropland originating from irrigation water) are 3250 km^3 yr^{-1} and 1530 km^3 yr^{-1}, respectively.

The global crop water model GCWM was developed by *Siebert and Döll* [2008, 2010] to solve the global soil water balance over the period 1998-2002, and to compute crop-specific evapotranspiration and irrigation water consumption of the 26 crop classes considered in the MIRCA2000 [*Portmann et al*., 2008, 2010] data set. Climate data was obtained from the CRU TS 1.0 [*New et al*., 2000, 2002] and the CRU TS 2.1 [*Mitchell and Jones*, 2005] climate databases. Three methods are employed to calculate the reference potential evapotranspiration: it is first computed using the FAO Penman-Monteith equation, then with the Priestley-Taylor equation modified by *Shuttleworth* [1993] (noted PM-Sh), and finally with the Priestley-Taylor equation, modified in the same way than in the global vegetation LPJmL model [*Bondeau et al*., 2007; *Rost et al*., 2008] (referred to as PM-LPJmL). The resulting GCWM model estimates of annual irrigation water requirements are 1821 km^3 yr^{-1} (Penman-Monteith), 2107 km^3 yr^{-1} (PM-Sh), and 1862 km^3 yr^{-1} (PM-LPJmL) (average is 1930 km^3 yr^{-1}). Estimates of irrigation water consumption are 902 km^3 yr^{-1} (Penman-Monteith), 1148 km^3 yr^{-1} (PM-Sh), and 911 km^3 yr^{-1} (PM-LPJmL) (average is 987 km^3 yr^{-1}). Figure 2.1 shows the average values resulting from the use of the three reference potential evapotranspiration calculation methods.

In a subsequent study, *Siebert et al*. [2010] used the GCWM model to compute irrigation water requirements with climate data for the period 1998-2002, accounting for different water sources: surface water, groundwater, and non-conventional water sources (i.e., wastewater or desalinated water). Irrigation water consumption was taken as the difference between potential crop evapotranspiration and water-limited actual evapotranspiration of the same crop under rainfed conditions. Reference potential evapotranspiration was computed with the Penman-Monteith equation [*Allen et al*., 1998], which was then multiplied by a crop and growing stage specific factor to obtain potential crop evapotranspiration. The origin of water for irrigation was determined using ratios of areas actually irrigated with surface water, with groundwater, or with non-conventional sources. Data on these areas were collected from national census reports, online databases, the FAO-AQUASTAT library, other organizations (e.g., Eurostat), the literature, and were complemented with data from the GMIA version 4 [*Siebert et al*., 2005]. *Siebert et al*. [2010] evaluated that global annual irrigation water consumption is 1277 $km^3\ yr^{-1}$.

The model PCR-GLOBWB was developed by *Van Beek and Bierkens* [2009] and *Van Beek et al*. [2011], and used by *Wada et al*. [2011b] to compute water demand and water stress at the global scale over the period 1958-2001. Irrigation water demand was computed using the monthly agricultural land use MIRCA2000 data set [*Portmann et al*., 2010] that provides information on irrigated areas around the year 2000 for 26 crop classes. Complementary crop data was retrieved from the GCWM data set [*Siebert and Döll*, 2008] (e.g., crop-specific evapotranspiration factors, rooting depth). Climate drivers were obtained from the CRU TS 2.1 global monthly climate data set [*Mitchell and Jones*, 2005]. Irrigation water requirements were computed as the difference between crop-specific potential and actual transpiration over irrigated areas, after calculating the reference potential evapotranspiration using the Penman-Monteith, and after separating potential bare soil evaporation and potential crop transpiration. Application losses are accounted for by including the effects of bare soil evaporation over the irrigated areas, while the losses that occur during water transport and the excess of water required to prevent salinization are included by applying an efficiency factor obtained from *Flörke and Alcamo* [2004]. Computed annual gross irrigation water requirements, averaged over the study period, are 2057 $km^3\ yr^{-1}$, and the estimated annual net irrigation water volume required to satisfy crop-specific transpiration is 1176 $km^3\ yr^{-1}$.

Using the global hydrological model WaterGAP [*Alcamo et al*., 2003], *Döll et al*. [2012] have performed an analysis of human activities effects on water resources for the period 1998-2002. The model computes direct and subsurface runoff, river discharge, groundwater recharge and storage variation, as well as the storage variation of water in the soil, surface water bodies, canopy, and snow. The location and the size of lakes, reservoirs and wetlands are retrieved from the global lakes and wetland database GLWD [*Lehner and Döll*, 2004] and from the man-made reservoirs data set of *Döll et al* [2009]. Crop growth periods for rice and non-rice crops are simulated in the model. Irrigation water consumption is equated as the difference between potential and actual crop evaporation, using data on irrigated areas from the FAO/University of Frankfurt Global Map of Irrigated Areas (GMIA) [*Siebert et al*., 2005, 2007]. Gross irrigation water requirements are estimated by multiplying the consumption rates with irrigation water use efficiencies, estimated for each country with data from three sources (i.e., *Kulkarni et al*. [2006], *Rohwer et al*. [2007], and *Aus der Beek* [2010]) [*Döll and Siebert*, 2002]. The effects of irrigated areas expansion over the 20th century are accounted for in the model by scaling the computed irrigation water consumption to annual time series of irrigated area per country, using the compilation of country irrigated area time-series for the period 1901-2010 from *Freydank and Siebert* [2008]. In areas equipped for irrigation, water is abstracted preferentially from groundwater and river storage. If these resources are not available, water is assumed taken from reservoirs, large lakes, and local lakes. If the irrigation water demand cannot be satisfied from water resources of the same grid cell, surface water is abstracted from a neighbouring grid cell. *Döll et al*. [2012] estimated that the annual volume of irrigation water required and irrigation water consumed during the period 1998-2002 is 3185 $km^3\ yr^{-1}$ and 1231 $km^3\ yr^{-1}$, respectively.

Wada *et al*. [2014] employed a newly developed irrigation scheme in which feedback between demand and supply and irrigation effects on surface water and groundwater are included. Unlike other studies, *Wada et al*. [2014] did not use project efficiency from available statistics but estimated irrigation efficiency dynamically, out of daily evaporative and percolation losses per unit crop area with the simulated surface and soil water balance of the model PCR-GLOBWB, thus not accounting for conveyance losses. Reference potential evapotranspiration is computed with the Penman-Monteith equation according to the FAO guidelines [*Allen et al*., 1998]. Paddy and non-paddy crops are distinguished in the computation of crop water requirements. Irrigated areas are described with the MIRCA2000 data set, and the 26 crop classes of MIRCA2000 were aggregated into paddy and non-paddy groups because paddy fields are mostly irrigated by flooding. Crop coefficients and additional crop data were obtained from the Global Crop Water Model data set [*Siebert and Döll*, 2010]. Climate drivers for the period 1979-2010 were retrieved from the ERA-Interim [*Dee et al*., 2011] and the MERRA reanalysis [*Rienecker et al.*, 2011] data sets. The precipitation, reference evapotranspiration, and temperature long-term monthly means of both climate data sets were scaled to those of the CRU TS 2.1 data set [*Mitchell and Jones*, 2005] for the overlapping period (1979-2010). Irrigation water requirements were simulated using the three climate data sets, and compared with country statistics from the FAO AQUASTAT database. *Wada et al*. [2014] estimated that over the period 1979-2010, global annual irrigation water requirements are 2885 km^3 yr^{-1} (CRU TS 2.1), 2614 km^3 yr^{-1} (ERA-Interim Reanalysis), 2217 km^3 yr^{-1} (MERRA reanalysis), 2572 km^3 yr^{-1} (average CRU TS 2.1, ERA-Interim and MERRA reanalysis), and 2416 km^3 yr^{-1} (average ERA-Interim and MERRA reanalysis). Model results tend to be overestimated with the CRU TS 2.1 climate, while this overestimation is less significant when using the ERA-Interim and MERRA reanalysis data set. Hence, *Wada et al*. [2014] have decided to use the average of the results simulated with the ERA-Interim and MERRA reanalysis data sets for further analysis. Estimated global annual irrigation water consumption is 1179 km^3 yr^{-1} (CRU TS 2.1), 1120 km^3 yr^{-1} (ERA-Interim reanalysis), 994 km^3 yr^{-1} (MERRA reanalysis), and 1057 km^3 yr^{-1} (average ERA-Interim and MERRA reanalysis). Figure 2.1 shows the average values of irrigation water requirements and consumption simulated with the three climate data sets used in the study.

Global water abstractions and consumption over the periods 1960-2010 and 2011-2099 were simulated by *Wada and Bierkens* [2014]. In this study, the global hydrological model PCR-GLOBWB [*Van Beek et al*., 2011; *Wada et al*., 2014] was forced with climate drivers from the ERA-40 re-analysis data set [*Kållberg et al.*, 2005; *Uppala et al*., 2005] for the period 1960-1978, from the ERA-Interim re-analysis [*Dee et al*., 2011] for the period 1978-2010, and from five global climate models and one emission scenario for the period 2011-2099. Reference evapotranspiration for the historical period 1960-2010 was computed with the Penman-Monteith equation according to the FAO guidelines [*Allen et al*., 1998]. *Wada and Bierkens* [2014] estimated that over the period 1960-2010, global water withdrawal increased from ~ 1700 km^3 yr^{-1} to ~ 4000 km^3 yr^{-1}, while global human water consumption increased more than two-fold, from ~ 800 km^3 yr^{-1} to ~ 2000 km^3 yr^{-1}. Over the period 1960-2010, irrigation water withdrawal increased from ~ 1280 km^3 yr^{-1} to ~ 2645 km^3 yr^{-1}. Further, *Wada and Bierkens* [2014] evaluated that most of the increase in water consumption is attributable to water consumption for irrigation purposes, which grew from ~ 655 km^3 yr^{-1} in 1960 to ~ 1390 km^3 yr^{-1} in 2010. Focusing on the representative concentration pathway (RCP) [*Van Vuuren et al*., 2011] 6.0 (i.e., the emission scenario that corresponds to a global increase of ~ 4 ° by the end of the 21st century), future irrigation water consumption was estimated for the current irrigated areas, thus representing the effects of climate change only. Global climate models were retrieved from the newly available coupled model intercomparison project phase 5 (CMIP5; http://cmip-pcmdi.llnl.gov/cmip5/) through the framework of the inter-sectoral impact model intercomparison project (ISI-MIP; www.isi-mip.org/). By the end of the 21st century (i.e., 2099), global human water withdrawal and consumption are projected to increase to ~ 6000 km^3 yr^{-1} and ~ 3000 km^3 yr^{-1}, while irrigation water withdrawal and consumption should increase from ~ 2645 km^3 yr^{-1} and ~ 1390 km^3 yr^{-1} in 2010 to ~ 3665 km^3 yr^{-1} and ~ 1650 (± 130) km^3 yr^{-1}, respectively, due to rising temperatures and associated higher evaporative demand (without including increasing atmospheric CO_2 concentration effects on crop growth and crop transpiration).

3.4 Previous work on irrigation efficiency

Bos and Nugteren [1990] introduced the "most widely accepted" definition of irrigation water efficiencies [*SanaeeJahromi et al*., 2001; *Rohwer et al*., 2007]. According to this definition, irrigation efficiency consists of the ratio of net to gross irrigation water requirements, ranging from 0 to 1. An irrigation efficiency factor of 1 corresponds to the consumption by the crops of the totality of water applied, while an irrigation efficiency factor of 0 means that no water abstracted is productively consumed, hence that the totality of water withdrawn is redirected back to the environment (i.e., the atmosphere, surface water and groundwater compartments). Net irrigation water needs are equated as the difference between potential and actual crop evapotranspiration, and gross irrigation water requirements are taken as the actual amount of water that needs to be abstracted from water sources, including losses that occur during conveyance, distribution, and application of water from the source to the crop fields.

Bos and Nugteren [1990] described irrigation efficiency as a combination of conveyance, distribution, and field application partial efficiencies. The conveyance efficiency is the ratio of the volume of water abstracted from a source or diverted to the volume of water delivered to the distribution system. The volume of conveyance losses depend on the type and the quality of water transport infrastructure (i.e., open canals, closed conduits or piped systems, pressurized pipeline systems), and the degree of technological management. As mentioned by *Rohwer et al*. [2007], a conveyance system without any losses is unlikely. Hence conveyance efficiency is always below 1. The distribution efficiency corresponds to the ratio of the water volume supplied to the distribution system from the conveyance network to the volume provided to the crop fields. It depends on the type and the quality of water distribution canals and conduits used for water distribution to the fields [*Bos and Nugteren*, 1990; *Rohwer et al*., 2007]. Distribution efficiencies range from 0.7 where surface irrigation systems with open canals prevail to 0.95 in countries with well-maintained pressurized pipeline systems

[*Rohwer et al*., 2007]. The third partial irrigation efficiency, the field application efficiency, is a measure of the performance of irrigation systems at watering plant roots and is equated as the ratio of the volume of water furnished at the inlet of cultivated fields to the volume actually made available to the crops. Field application efficiency is dependent on the type of irrigation practiced (i.e., surface irrigation, sprinkler irrigation, micro-irrigation). It ranges from 0.6 in countries where surface irrigation (i.e., flooding) prevails to 0.9 in countries equipped for micro-irrigation (i.e., dripping) [*Rohwer et al*., 2007].

Project efficiencies were computed in a similar way by *Rohwer et al*. [2007]. However, the distribution efficiency was replaced by a field management factor due to the deficiency or low reliability of data on distribution systems efficiency. Field management is described based on the type of irrigation system at the disposal of the irrigator (i.e., surface irrigation, sprinkler, or micro-irrigation) and the scale of the irrigation system (i.e., from small to expended large scale systems). Generally, the degree of management of an irrigation system decreases with the size of the irrigation project, thus the field management factor ranges from 0.7 for countries with mainly large-scale surface irrigation schemes to 1 in countries with small-scale irrigation systems.

The project efficiency of an irrigation system results from the combination of the three partial efficiencies [*Bos and Nugteren*, 1990; *Rohwer et al*., 2007]. Therefore, the project efficiency of an irrigation system stands for the ratio of the total water volume abstracted or diverted from the source for irrigation purposes to the volume of irrigation water actually made available for productive crop evapotranspiration [*Bos and Nugteren*, 1990; *Döll and Siebert*, 2002, *Rohwer et al*., 2007; *Aus der Beek*, 2010; *Döll et al*., 2012]. Project efficiencies are higher than 0.8 in countries with predominantly micro-irrigation and ~ 0.3 in countries with poorly managed large-scale surface irrigation systems [*Rohwer et al*., 2007].

Most recent hydrological model studies have included irrigation efficiency in the computation of gross irrigation water requirements. The modeling strategy to account for irrigation efficiency differs among the GHMs and MHMs.

Döll and Siebert [2002] first computed net irrigation water requirements, or irrigation water demand needed to enable maximum crop potential crop evapotranspiration, as the difference between potential crop evapotranspiration and actual crop evapotranspiration under natural conditions (i.e., without irrigation). Gross irrigation water requirements were subsequently estimated by multiplying net irrigation water demand by project efficiencies. *Döll and Siebert* [2002] compiled project efficiencies of irrigation water use for different regions of the world from various sources, among which the project efficiency data of *Bos and Nugteren* [1978, 1990], FAO [1997] estimates for African countries, and data of *Guerra et al*. [1998] for South and Southeast Asia.

Similarly, *Rost et al*. [2008] and *Wisser et al*. [2010] have computed gross irrigation water demand based on the multiplication of net irrigation water requirements with irrigation water efficiencies. *Rost et al*. [2008] used the country-scale irrigation efficiency data set of *Rohwer et al*. [2007], and *Wisser et al*. [2010] retrieved irrigation efficiency country averaged numbers from FAO AQUASTAT [2008] and *Döll and Siebert* [2002].

In the study of *Wada et al*. [2011b], gross irrigation water requirements were determined by multiplying the sum of bare soil evaporation and irrigation crop water requirements by an irrigation efficiency factor [*Flörke and Alcamo*, 2004]. Bare soil evaporation over irrigated areas, computed as the difference between simulated potential bare soil evaporation and simulated actual bare soil evaporation, was added to irrigation crop water requirements in order to include losses during irrigation water application. The efficiency factor was set to 1.2, that is, 20 % more irrigation water has to be applied to prevent soil salinization and to account for evaporation losses during transport and application.

Gross irrigation water requirements were computed by *Döll et al*. [2012] by multiplying crop net irrigation water requirements with country irrigation efficiency factors. Irrigation water use efficiencies were estimated from several sources, i.e., from *Kulkarni et al*. [2006], *Rohwer et al*. [2007], and *Aus der Beek* [2010] reports on irrigation efficiency.

Hanasaki et al. [2013] performed a water scarcity study for the 21st century in which water use scenarios compatible with the five shared socio-economic pathways (SSPs) were made to represent developments in industrial and domestic water demands, irrigated areas, crop intensity, and irrigation efficiency. The shared socio-economic pathways are used in global climate change studies to illustrate future global situations such as demographic evolution or future electricity consumption and production [*Kriegler et al*., 2012; *O'Neill et al*., 2012]. However, SSPs do not quantitatively or qualitatively describe future water use, hence the necessity to develop scenarios of future water requirements and consumption. Changes in irrigation areas, crop intensity, and irrigation efficiency were described by *Hanasaki et al*. [2013] using scenarios from previous studies (i.e., *Rosegrant et al*., 2002; *Bruinsma*, 2003; *Alcamo et al*., 2005; *De Fraiture et al*., 2007; *Rosegrant et al*., 2009). *Hanasaki et al*. [2013] assumed that irrigation efficiency upper boundary is 1.0 and that irrigation, industrial and municipal water efficiencies are correlated with the technological evolution described in the SSPs. Technology is assumed low for SSP3, medium for SSP2, and high for SSP1 and SSP5. The SSP4 describes technology as low and stationary in developing countries, and high in developed countries. Therefore, ratios of irrigation efficiency development over the 21st century were set by *Hanasaki et al*. [2013] to 0.30 % yr^{-1} for the SSP1 and SSP5, 0.15 % yr^{-1} for the SSP2, and 0 % yr^{-1} for the SSPS3 and SSP4. Irrigation water use efficiencies for the benchmark year 2000 from *Döll and Siebert* [2002] multiplied with the irrigation efficiency growth ratios yielded future irrigation efficiencies.

Instead of using project efficiencies from available irrigation water use efficiencies data sets (e.g., *Bos and Nugteren* [1990], *Döll and Siebert* [2002], *Rohwer et al*. [2007]), *Wada et al*. [2014] directly estimated irrigation efficiency from the surface and soil water balance, based on daily losses of water to the atmosphere (i.e., evaporation losses) and to the soil lower compartments (i.e., percolation losses). Therefore, this modeling strategy only accounts for irrigation water application efficiency (i.e., the amount of water actually made available to the crops), and neglects conveyance and distribution partial efficiencies.

3.5 Partitioning between different water sources for irrigation

Water intended for cultivation comes from three sources: green water (i.e., soil moisture replenished with local rainfall), blue water (i.e., surface water stored in rivers, artificial reservoirs or lakes, wetlands, and renewable groundwater), and non-renewable groundwater and non-local water resources [*Vörösmarty et al*., 2005; *Wada et al*., 2012a]. Non-local water corresponds to water transported from another catchment (i.e., cross-basin diversions), and water from desalinization plants. Groundwater resources are subdivided into renewable groundwater and non-renewable groundwater, based on the exploitation intensity of the aquifer: when the exploitation of an aquifer and its recharge rate are imbalanced, non-renewable groundwater is abstracted in surplus of the recharge, leading to groundwater levels depletion [*Wada et al*., 2010], while renewable groundwater corresponds to the volume of abstracted groundwater compensated by natural and artificial recharge to the aquifer.

The concept of non-renewable and non-local water resources was introduced by *Vörösmarty et al*. [2005] who estimated that non-renewable and non-local water abstractions under contemporary conditions range from 389 $km^3 yr^{-1}$ to 830 $km^3 yr^{-1}$. It has been described as non-renewable and non-local blue water resources (NNBW) [*Rost et al*., 2008; *Hanasaki et al.*, 2010], or non-renewable groundwater and non-local water resources (NRGNLW) [*De Graaf et al*., 2014]. Other recent studies that consider the various effects of irrigation activities on groundwater resources do not explicitly include non-local water resources due to the limited availability of global data on non-local water abstractions [*Wada et al*., 2014; *Wada and Bierkens*, 2014].

Over the last decade, non-renewable groundwater and non-local water resources have increasingly been incorporated in global hydrological studies (e.g., *Vörösmarty et al*. [2005], *Rost et al*. [2008], *Hanasaki et al.* [2010], *Siebert et al.* [2010], *Wada et al*. [2010], *Döll et al*. [2012], *Wada et al*. [2012a]). This trend results from the necessity of evaluating the real impact of human activities, since it became clear that the influence of domestic, industrial, and especially irrigation activities on water resources depends on the type of water source it is abstracted from [*Vörösmarty et al*., 2000; *Döll and Siebert*, 2002; *Alcamo*, 2003; *Wisser et al*., 2008; *Wada et al*., 2010, 2011b, 2012a; *Siebert et al*., 2010; *Anderson et al*., 2012]. Anterior hydrological studies could not explicitly account for the actual impact of human activities on water resources and deliberately did not include them in their computational procedure, or assumed these resources limitless due to the deficiency of data on the capacity of each source (e.g., [*Haddeland et al*., 2006b; *Rost et al*., 2008; *Hanasaki et al*., 2008, 2010].

Globally, 38 % of the area equipped for irrigation is equipped for groundwater irrigation while the area actually under groundwater irrigation amounts to 39 % of the total area actually irrigated [*Siebert et al*., 2010]. Groundwater resources represent a more reliable and accessible source of water than surface water, especially in intensively irrigated areas. However, apart from FAO country-based statistics, little information exists on the allocation of surface water and groundwater to irrigation water supply. Similarly, the volume of non-renewable groundwater or non-local water abstracted for irrigation purposes is poorly documented. Nevertheless, irrigation accounts for 70 % of total water withdrawal and 90 % of consumptive water use [*Shiklomanov and Rodda*, 2003; *Vörösmarty et al*., 2005; *Rost et* *al.*, 2008; *Rockström et al.*, 2009; *Wada et al.*, 2011b; *Wada et al.*, 2014]. Evaluating the volume and the magnitude of the impact of irrigation water abstractions and consumption on the water resources is urgently needed. For example, groundwater levels depletion results from the overexploitation of the groundwater storage, leads to a decrease in base river flow [*Gleeson et al*., 2010], and can cause important damages to the ecosystem downstream and any local human population. Such phenomenon threatens water resources sustainability and requires particular attention. Due to the lack of data, most previous hydrological studies had to make assumptions on the attribution rules of a water resource to irrigation water supply.

In order to evaluate the contribution of non-renewable and non-local blue water to agriculture, *Rost et al*. [2008] carried out simulations of the hydrological cycle under two scenarios: in one scenario, potential crop evapotranspiration is assumed always satisfied. Once water storage in rivers, lakes and reservoirs is depleted, irrigation water requirements are met from non-renewable and non-local blue water resources, which are assumed limitless. In the second scenario, non-renewable and non-local blue water resources are neglected, since it is not possible to explicitly include these resources. This is due to the inability of the routing scheme to include river diversions and to the little amount of information available at the global scale on groundwater. In this simulation, irrigation water requirements are restricted to the simulated volume of water available as renewable groundwater, in rivers, lakes, and reservoirs. The difference between the two model runs represents an estimate of the withdrawal and consumption of non-renewable and non-local water resources. *Rost et al*. [2008] estimated that total non-renewable and non-local irrigation blue water withdrawal and consumption are ~ 1400 km^3 yr^{-1} and 730 km^3 yr^{-1}, respectively.

Similarly, *Wisser et al*. [2010] did not explicitly include non-renewable groundwater resources in their study. These resources were assumed infinite and exploited once irrigation water demand cannot be satisfied using water stored in reservoirs, renewable groundwater or local discharge. In addition, non-local water abstractions were not accounted due to the lack of global information on cross-basin water transfers. *Wisser et al*. [2010] used different rules for the attribution of irrigation water supply, assuming irrigation water is abstracted first from reservoirs, then from non renewable groundwater resources, and finally from surface water. Renewable groundwater is simulated by a simple runoff retention pool that delays runoff and stores excess water from the vertical water budget. *Wisser et al*. [2010] estimated that the volume of irrigation water requirements for the year 2002 amounts to 2997 km^3 yr^{-1}, of which ~ 1200 km^3 yr^{-1} (~ 40 %) are abstracted from non-renewable water resources.

Inversely, *Hanasaki et al*. [2010] considered that irrigation water is abstracted first from surface water resources. Non-renewable and non-local water resources were assumed available anytime, anywhere, after irrigation water requirements were first met from river discharge and reservoirs. This assumption is comparable to that of *Rost et al*. [2008] and *Wisser et al*. [2010], and stems from the scarcity of global data on these water resources. Shallow groundwater (i.e., renewable) is incorporated in runoff because the land surface hydrology module of the H08 model only separates precipitation into evapotranspiration and runoff. Water stored in lakes, glaciers, and non-renewable (i.e. fossil) groundwater could not be included in the simulation since these water resources develop beyond the temporal scale of the model. Likewise, it was not possible to account for non-local water resources because water diversion and desalinization activities transport water beyond grid cells. Over the period 1985-1999, *Hanasaki et al*. [2010] estimated that 703 km^3 yr^{-1} of non-renewable and non-local water are required to satisfy the totality of irrigation water requirements.

To represent the contribution to irrigation of different water sources, *Siebert et al*. [2010] used ratios of area equipped for irrigation (AEI) with groundwater, surface water, or non-conventional water (i.e., wastewater or desalinated water) to total AEI, and ratios of area actually irrigated (AAI) with groundwater, surface water, or non-conventional water to total AAI. Data on the global AEI and AAI was collected from several sources, including national census reports, the FAO AQUASTAT database, the literature, and other organizations such as Eurostat. Total AEI estimated by *Siebert et al*. [2010] is 301 million ha. Of this amount, ~ 84 % (i.e., 253 million ha) of total AEI is actually irrigated. ~ 38 % (i.e., 113 million ha) of the total AEI is equipped for irrigation with groundwater, and groundwater is actually supplied over 39 % (i.e., 98 million ha) of total AAI. *Siebert et al*. [2010] estimated that groundwater consumption for irrigation purposes averaged over the period 1998-2002 amounts to 545 km^3 yr^{-1}, while non-conventional water (i.e., wastewater or desalinated water) withdrawal averaged over the same period is 1.5 km^3 yr^{-1}.

In order to evaluate global groundwater resources depletion, *Wada et al*. [2010] used the Global Groundwater Information System database from the International Groundwater Resources Assessment Centre (IGRAC, www.un-igrac.org). Population statistics of the year 2000 were used to update groundwater withdrawals, and abstraction rates per country were attributed to the corresponding groundwater region. Based on the assumption that groundwater is abstracted close to where it is required, *Wada et al*. [2010] used a global yearly water demand map as a proxy to downscale groundwater abstraction to 30 min resolution. *Wada et al*. [2010] estimated that global groundwater recharge and abstractions for the year 2000 amount to $15.2 \cdot 10^3$ km^3 yr^{-1} and 734 (±82) km^3, respectively. Simulated global gross irrigation water requirements are 2057 km^3 yr^{-1}, of which 1478 km^3 yr^{-1} are satisfied with surface water and renewable groundwater abstractions. Based on these figures, ~ 580 km^3 yr^{-1} of irrigation water requirements have to be satisfied from non-renewable groundwater and non-local water resources. Hence, *Wada et al*. [2010] estimated that total non-renewable groundwater contribution (i.e., global depletion of groundwater resources) to gross irrigation water demand amounts to 283 (±40) km^3 yr^{-1}.

In the continuity of this study, *Wada et al*. [2012] further investigated the supply of non-renewable and non-local water resources for irrigation. In this study, it was estimated that, for the year 2000, 1338 km^3 yr^{-1} of water were required to satisfy gross irrigation water requirements. Over the year 2000, *Wada et al*. [2012] evaluated that the contribution of blue water, non-renewable groundwater, and non-local water resources to gross irrigation water requirements amounted to 63 % (i.e., 844 km^3 yr^{-1}), 18 % (i.e., 234 km^3 yr^{-1}), and 19 % (i.e., 260 km^3 yr^{-1}), respectively.

Recent studies have introduced new methods to account for the allocation of surface water and groundwater to water requirements.

Döll et al. [2012] have included return flows of surface water and groundwater abstractions to the surface water or groundwater compartments, and have considered that in areas equipped for irrigation groundwater and water stored in rivers are exploited first. Diffuse groundwater recharge via the soil is included in the simulation. However, focused groundwater recharge from rivers, lakes and wetlands is not included in the study due to the poor representation of direct recharge processes. Sectoral groundwater uses (i.e., for irrigation, domestic, and industrial purposes) were evaluated by multiplying simulated consumptive and withdrawal water uses in each grid cell by a temporal invariant groundwater use fraction. Groundwater fractions for irrigation were defined by considering the ratio of area equipped for irrigation with groundwater to total irrigated area. These ratios are based on data for 15038 national and subnational spatial statistical units. Areas equipped for irrigation were described using statistics from national census reports, online databases complemented with country information from the FAO AQUASTAT database, the literature, and other institutions or statistical services. Averaged over the period 1998-2002, *Döll et al*. [2012] estimated that groundwater represents 42 % (i.e., 1337 km^3 yr^{-1}) of global irrigation water withdrawal, and 43 % (i.e., 529 km^3 yr^{-1}) of global irrigation water consumption.

Previous models were generally employed to compute water demand without taking into account actual water availability per source. Water demand and water availability were commonly computed separately, and subsequently confronted. *De Graaf et al*. [2014] developed a dynamic attribution scheme which was implemented in the PCR-GLOBWB model to compute surface water and groundwater withdrawal and consumption. Figure 2.1 presents the model concept of the PCR-GLOBWB model and the dynamic allocation scheme used in *De Graaf et al*. [2014]. The prescribed irrigation scheme accounts for the actual availability of surface water and groundwater, the effects of human water abstractions and return flows on water availability, and includes drainage of groundwater to surface water and groundwater recharge through infiltration of surface water. However, non-renewable groundwater and non-local water (noted NRGNLW) resources, exploited when no renewable water is available, are assumed unlimited and are calculated as negative groundwater storage (i.e., as the difference between simulated total groundwater withdrawal and renewable groundwater abstractions). If both surface water and groundwater groundwater resources are available, the attribution of these resources to water demand is determined by several factors: feedbacks from return flows, infiltration of surface water to the groundwater compartment through the riverbed and drainage of groundwater to surface water bodies. *De Graaf et al*. [2014] run the model under three scenarios: no abstractions (i.e., no human impact), abstractions without return flows, and return flows in addition to water abstractions. The objective of using various scenarios is to evaluate the effects of abstractions and return flows on river discharges, on the attribution of water resources, and ultimately on the availability of each water resource. Under the abstractions only scenario, *De Graaf et al*. [2014] estimated that surface water and groundwater abstractions increased from ~ 445 km^3 yr^{-1} and ~ 460 km^3 yr^{-1} (of which ~ 285 km^3 yr^{-1} are from NRGNLW resources) in 1960 to ~ 1000 km^3 yr^{-1} and ~ 980 km^3 yr^{-1} (of which ~ 560 km^3 yr^{-1} are from NRGNLW resources) in 2010, respectively. Including return flows results in higher surface water abstractions and in lower NRGNLW abstractions: surface water and groundwater abstractions increased from ~ 450 km^3 yr^{-1} and ~ 465 km^3 yr^{-1} (of which ~ 195 km^3 yr^{-1} are from NRGNLW resources) in 1960 to ~ 1115 km^3 yr^{-1} and ~ 950 km^3 yr^{-1} (of which ~ 430 are from NRGNLW resources) in 2010, respectively. To limit NRGNLW, groundwater localized 100m below the surface was assumed unattainable. Therefore, nearly 150 km^3 yr^{-1} of groundwater cannot be abstracted for the year 2000 and have to be satisfied by non-local water resources or deeper aquifers.

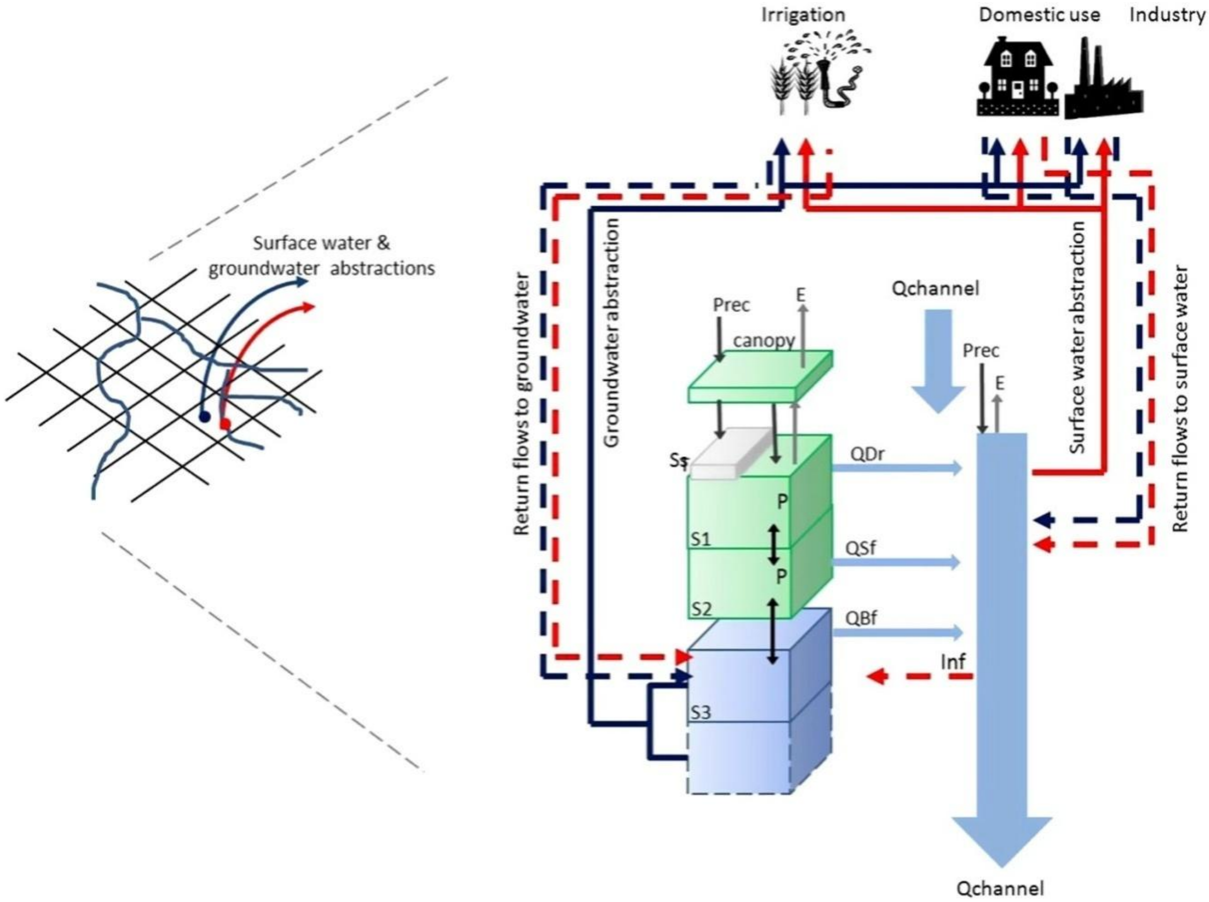

Figure 3-2: Model concept of PCR-GLOBWB and used allocation scheme. Middle part: the soil compartment, divided into two soil layers (S1 and S2) and one linear groundwater reservoir (S3). Precipitation (Prec) falls as rain or snow (temperature dependent) and can be stored in canopy or as snow accumulation (Ss). Vertical transport within the soil column occurs through percolation or capillarity rise (P). The total local gains from all cells, i.e. drainage (QDr), subsurface flow (QSf), and baseflow (Qbf), are routed along the drainage direction to yield the channel discharge (Qchannel). In every grid cell water can be abstracted from surface water or groundwater. Return flows go to surface water or groundwater, dependent on the water use. From *De Graaf et al*. [2014].

Renewable groundwater resources were estimated by *Wada et al*. [2014] with the PCR-GLOWB model as the ratio of simulated daily baseflow (Q_{Bf} from compartment S3 in Figure 2.1) to simulated long-term average river discharge, multiplied afterwards by total water demand. Water is first withdrawn from reservoirs, if some are situated locally or upstream over the river network, and from surface water. Any remaining water demand is met from available groundwater storage. When no surface water and renewable groundwater is available, water demand is first met from non-renewable groundwater resources. Available water resources are supplied proportionally to sectoral water demand, without any priority given to a specific sector (i.e., livestock, irrigation, domestic, and industrial water demand sectors). Irrigation water returns to the soil layer by infiltration and to the groundwater as artificial groundwater recharge. *Wada et al*. [2014] estimated that over the period 1979-2010, surface water and groundwater withdrawal increased by 2 % per year and 1 % per year, respectively, i.e., from ~ 1350 km^3 yr^{-1} to ~ 2100 km^3 yr^{-1} (surface water) and from ~ 650 km^3 yr^{-1} to ~ 1200 km^3 yr^{-1} (groundwater). Groundwater withdrawal in the year 2000 amounted to

~ 1000 km^3 yr^{-1}. However, over the period 1990-2010, groundwater withdrawal rate increased of ~ 3 % per year while surface water withdrawal rate decreased to ~ 1 %.

Using the global hydrological PCR-GLOBWB model [*Van Beek et al.*, 2011; *Wada et al.*, 2014], *Wada and Bierkens* [2014] estimated that total groundwater abstractions have significantly increased over the period 1960-2010, from ~ 370 km^3 yr^{-1} in 1960 to ~ 950 km^3 yr^{-1} in 2010, of which ~ 25 % (~ 90 km^3 yr^{-1}) in 1960 and ~ 32 % (~ 300 km^3 yr^{-1}) in 2010 were non-renewable groundwater. In 1960, ~ 20 % of the total water consumption was satisfied by surface water over-abstractions (~ 80 km^3 yr^{-1}) and non-renewable groundwater abstractions (~ 90 km^3 yr^{-1}). Surface water over-abstractions correspond to the amount of environmental flow required to sustain ecosystem services that cannot be satisfied because of local and upstream surface water abstractions and consumption. In 2010, the consumption of non-sustainable surface water and non-renewable groundwater increased to ~ 30 % of the total water consumption, with ~ 270 km^3 yr^{-1} (~ 47 % of total non-sustainable water consumption) of non-sustainable surface water and ~ 300 km^3 yr^{-1} (~ 53 % of total non-sustainable water consumption) of non-renewable groundwater consumed. *Wada and Bierkens* [2014] noted that in 2010, agriculture water requirements, mainly for irrigation purposes, represented ~ 75 % of total groundwater abstractions globally, and more than 80 % of total groundwater abstractions intended for agricultural activities in five major groundwater users (i.e., 89 % in India, 90 % in Pakistan, 90 % in Iran, 90 % in Saudi Arabia, and 80 % in Mexico). Over the period 2011-2099, non-sustainable water resources consumption is projected to increase to ~ 1100 (± 200) km^3 yr^{-1}, with ~ 500 (± 100) km^3 yr^{-1} (~ 45 ± 10 % of total non-sustainable water consumption) of non-sustainable surface water and ~ 600 (± 85) km^3 yr^{-1} (~ 55 ± 10 % of total non-sustainable water consumption) of non-renewable groundwater consumed.

3.6 Effects of irrigation on water availability

Advances in hydrological modeling have helped refining the scientific knowledge on natural hydrological cycle processes and on anthropogenic impacts on water resources. Due to the relatively recent development of information on groundwater abstraction [*Rost et al.*, 2008; *Wada et al.*, 2010] and withdrawals differentiated by source [*Döll et al.*, 2012], only most recent studies could explicitly include the actual impact of human water abstractions and consumption. Improvements in the inclusion of human water use in macro-scale and global-scale hydrological models led to a better, more comprehensive assessment of human activities effects on water resources.

Wisser et al. [2010] performed a reconstruction of the 20th century global hydrography using the WBM$_{plus}$ model and observed a steady upward trend for all continents over the study period in irrigation water use that reflects the expansion of irrigated areas over the last century. However, no detailed data set of withdrawal per water source was available to help differentiate the impacts of water abstraction from the surface water or groundwater compartment [*Oki and Kanae*, 2006]. It was estimated that over the 20th century, irrigated areas expansion significantly increased evapotranspiration (e.g., in Eastern China, India, and

Central America) due to land cover changes [*Vörösmarty*, 2002], and that these changes translate to decreases in runoff in Eastern China and India. *Wisser et al.* [2010] estimated that human activities, primarily irrigation activities and irrigated areas expansion, were responsible for a decrease of global discharge at the beginning and at the end of the 20th century of 0.6 % and ~ 2 %, respectively. Irrigation activities, irrigated areas expansion, and streamflow changes imposed by the construction of reservoirs may have dramatic impacts in individual river basins. However, global discharge to the oceans is not significantly degraded by human activities and is mainly governed by climate variations.

Most major rivers in the world being regulated by artificial reservoirs [*Vörösmarty et al*., 2000, 2004; *Nilsson et al*., 2005] to retain discharge for irrigation purposes or controlled release (i.e., flood control, hydropower, navigation, and other sector water supply), *Van Beek et al*. [2011] evaluated the impact of large dams on streamflow. It was estimated in this study that reservoir regulation itself hardly affects long-term mean annual discharge, but that water supply from artificial lakes has a pronounced negative impact on water storage in rivers, in particular over major irrigated areas of the world (e.g., Central North America, Spain, India, and east China). *Van Beek et al*. [2011] estimated that irrigation activities represent the main cause for the increase in water demand over heavily irrigated regions (e.g., irrigation water demand has more than doubled over the period 1960-2000 in India and amounts to ~ 90 % of total Indian's water demand [*Wada et al*., 2011a,b]) and that most areas experiencing frequent and persistent water stress are associated with a strong irrigation water demand (e.g., Central North America, India, northern China [*Wada et al*., 2011b]). In regions with limited access to surface water or overlying productive aquifers, groundwater is often the main source of irrigation water. *Wada et al*. [2012a] reported large groundwater abstractions over irrigated hotspots (e.g., India, northern China, Pakistan, and USA). In addition, *Wada et al*. [2011a, 2012a] have characterized the strong increase since 1960 in non-renewable groundwater abstractions as a result of the development of irrigated areas, particularly in semiarid regions where scarce surface water resources for irrigation are subject to a severe competition between users [*Döll et al*., 2012]. Furthermore, *Chao et al*. [1998] reported a reduction in the rate of increase of artificial reservoir capacities since the 1990s, ultimately leading to a growing dependency of irrigation activities on non-renewable water resources.

Döll et al. [2012] reported the prominence of water abstractions in semi-arid and arid regions, with often more than 95 % of total water withdrawal in these areas intended for irrigation purposes. In addition, water consumptive use was found to be even more strongly concentrated in extensively irrigated semi-arid and arid areas than water abstractions. *Döll et al*. [2012] observed in many areas the balance between surface water and groundwater abstractions for irrigation, that is, in regions where surface water use is dominant, groundwater storage is increased (e.g., Nile basin, lower Indus basin, Southeastern China), and in regions where groundwater use prevails, surface water storage is increased (e.g., High Plains in central USA, Northeastern China). *Döll et al*. [2012] noted the significance of both surface water and groundwater abstractions in the Ganges basin, Southern India, California in the USA, and in Spain, as well as the major role played by return flows in the refilling of surface water and groundwater stores. *Döll et al*. [2012] assumed that return flows to groundwater only occur in irrigated areas and that the surface water and groundwater storages are affected by net abstractions (i.e., the difference between withdrawals and the sum of return flows and natural recharge to the groundwater compartment).

Significant impact of water abstractions on water resources were reported in irrigated basins by *Gleeson et al.* [2012] and *De Graaf et al.* [2014], in particular the degradation of streamflow (e.g., low flows decreased by 25 to 50 % because of water abstractions in the Indus and Yellow River basins) and the prominence of non-renewable and non-local water use in these areas to sustain irrigation. However, the importance of irrigation return flow, up to 60 %, to the groundwater was demonstrated by *De Graaf et al*. [2014]: the redirection of water to a slow component (i.e., baseflow) leads to a greater baseflow component, increased renewable groundwater availability, hence to lower non-renewable groundwater and non-local water abstractions, and changes in timing and duration of low flows in irrigated regions.

Similarly, rivers crossing major irrigated areas of the world were also found significantly impacted by *Wada et al*. [2014]. In this study, simulated monthly terrestrial water storage anomalies were compared with those of the GRACE observations [*Liu et al.*, 2010] for river basins assumed heavily affected by human activities over the period 2003-2010 (i.e., the Nile, the Mekong, the Ganges, the Indus, the Yangtze, the Huang He, the Mississippi, the Orange, the Murray, the Columbia, and the Volga basins). Irrigation water abstractions are highly concentrated in intensively irrigated areas located in semi-arid and arid regions. Human activities alter regional terrestrial water storage signal, and its seasonal and interranual variations: reservoir releases are increased during low flow periods, and the peak terrestrial water storage signal and its seasonal amplitude are subject to a reduction due to surface water and groundwater abstractions, primarily for irrigation purposes during the crop growing season (e.g., over the Mississippi, the Colorado, the Columbia, the Indus, and the Nile basins). However, in some areas, negative groundwater storage may be compensated by return flow from irrigation (i.e., Nile basin). *Wada et al*. [2014] noted the increasing reliance of irrigators on groundwater over the past two decades, which can be explained by the scarcity of accessible surface water resources, and their intense exploitation over the past and contemporary conditions.

Wada and Bierkens [2014] introduced a new indicator of human water use impact on water resources: the blue water sustainability index (BlWSI). Anterior water scarcity and water availability indicators have weak points, among which the disregarding of non-renewable groundwater use and environmental flow requirements, and the rare projections of non-renewable groundwater use for future human water requirements. Therefore, the BlWSI indicator has been developed to include non-renewable groundwater and non-sustainable water uses and evaluate the sustainability of human water requirements and consumptive use [*Smakhtin et al*., 2004; *Vörösmarty et al.*, 2005]. The BlWSI indicator is measured for the period 1960-2099 by computing the ratio of non-renewable groundwater withdrawal and surface water over-abstractions to total consumptive blue water use (i.e., the sum of livestock, irrigation, industrial, and domestic water consumption). Surface water over-abstractions correspond to the fraction of water removed from the surface water compartment that needs to be present to sustain environmental and aquatic water requirements. This amount is characterized by Q_{90}, that is, the monthly streamflow exceeded 90 % of the time [*Smakhtin et al*., 2004] calculated under undisturbed or natural conditions (i.e., under a no abstraction scenario). Surface water over-abstractions are estimated by computing the difference between environmental flow requirements and human water consumption. *Wada and Bierkens* [2014] observed that over the historical period 1960-2010, human water consumption increased drastically for all water demand sectors, and that most of the increase is due to the intense irrigation water consumption in central and eastern Asia (i.e., North Iran, India, Pakistan, and China), Central and North America, southern Europe, and Nile delta. Together, these regions represent more than 90 % of global irrigated areas. Using the blue water sustainability index, significant amounts of non-sustainable surface water consumption (i.e., abstracted at the expense of environmental flow requirements) are observed over southern, western and Central Asia, Spain, Argentina, western and central USA, Mexico, and over the Nile and Murray-Darling basins. Further, BlWSI for groundwater is reportedly high over regions with the highest rates of irrigation water consumption (e.g., the Indus basin, Saudi Arabia, Iran, southwestern and central USA, and Northern Mexico), indicating that about half of the irrigation water consumption over these regions is sustained by non-renewable groundwater. This highlights the significant role of non-renewable groundwater to sustain irrigation water supply in areas with limited amount of precipitation, yet high irrigation water and high evaporative demand.

4. Methods

4.1 The PCR-GLOBWB model

In this study, the global-scale hydrological model PCR-GLOBWB (PCRaster GLOBal Water Balance) [*Van Beek et al.*, 2011; *Sutanudjaja et al.*, 2014] is used to simulate global water balance of the terrestrial part of the hydrological cycle (excluding Antarctica) at 0.5 × 0.5° or 30 arc min (about 50 km at the equator) grid-cell resolution globally. Water storages and exchanges are simulated between two vertically stacked soil layers and an underlying groundwater layer, as well as canopy interception and snow cover. Snow storage is simulated with the snow module of the HBV model [*Bergström*, 1995]. Exchanges with the atmosphere are also simulated (i.e., rainfall, evapotranspiration, and snowmelt).

The PCR-GLOBWB model accounts for human-induced impact on natural water resources by including livestock, industrial and domestic water abstractions and consumption. A dynamic irrigation scheme is included to compute daily surface water and groundwater irrigation water requirements per unit crop area for paddy and non-paddy crops. Irrigation water requirements for paddy crops are estimated based on the surface water balance, assuming that a water layer of 50 mm has to be maintained over paddy fields [*Wisser et al.*, 2008, 2010]. Irrigation water requirements are evaluated based on the soil moisture deficit in the root zone, computed as the difference between the water contents at field capacity and at wilting point [*Wada et al.*, 2014]. The PCR-GLOBWB model includes the effects of human water abstractions and of return flows on water resources, as well as the drainage of groundwater to surface water and the groundwater recharge through infiltration of surface water (see the PCR-GLOBWB model concept in figure 2.1) [*Wada et al*., 2011b, 2012a; *Winsemius et al*., 2013; *Wada et al*., 2014; *De Graaf et al*., 2014; *Sutanudjaja et al*., 2014].

Irrigated areas are described using the global data set of monthly irrigated and rainfed crop growing areas of 26 crop classes (i.e., cotton, all major food crops, perennial, annual and fodder crops) for the period 1998-2002 (MIRCA2000) [*Portmann et al*., 2010]. This data set explicitly considers multi-cropping practices: if a crop is grown more than once a year (i.e., double cropping, triple cropping, etc.), the sum of the growing areas of the subcrops equals the crop-specific total annual harvested area. Since paddy fields are mostly irrigated by flooding, the different crop classes considered in the MIRCA2000 data set were combined into paddy and non-paddy crop groups. Hence, crop water requirements are computed for paddy and non-paddy crops, and four land cover classes are considered in the model: two natural classes (i.e., forest, grassland), and two 'artificial' classes (i.e., paddy fields, non-paddy fields). Crop-related data (e.g., crop coefficients, effective rooting depth) was obtained from the GCWM data set of *Siebert and Döll* [2010].

The expansion of irrigated areas over the period 1960-2010 is represented in model simulations by using reported values of irrigated area per country for ~ 230 countries from the FAOSTAT database. These statistics are subsequently downscaled to 0.5° based on the spatial distribution of irrigated areas around the year 2000 from the MIRCA2000 data set. This method has been successfully applied in previous studies (e.g., *Wisser et al*. [2010], *Wada et al*. [2014]) to represent the historical growth of irrigated areas over large areas. However, it does not reflect changes in the distribution of irrigated areas within countries *Wada et al*. [2014]. Irrigated area extent has increased significantly after 1960 and has slowed down since the 1990's [*FAO*, 2006, 2012; *Wisser et al*., 2010; *Wada et al*., 2011b].

Soil types are described with the FAO Digital Soil Map of the World [FAO, 2003]. The improved Arno scheme [*Todini*, 1996; *Hagemann and Gates*, 2003] is used to compute the groundwater depth frequency distribution, based on the HYDRO1k Elevation Derivative Database [United States Geological Survey (USGS) Center for Earth Resources Observation and Science; http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/HYDRO1K].

Data on industrial and domestic water demand were retrieved from the study of *Wada et al*. [2011b]. In brief, industrial water demand for the year 2000 was taken from three sources (i.e., *Shiklomanov* [1997], *World Resources Institute* (WRI) [1998], and *Vörösmarty et al*. [2005]), and kept constant throughout the year. Time series of industrial water demand over the period 1960-2010 were computed by multiplying industrial water demand for the benchmark year 2000 by water use intensities derived from an algorithm developed by *Wada et al*. [2011a]. Gross domestic product, energy consumption, electricity production, and household consumption were combined in the algorithm to estimate economic development per country. Technological development per country was estimated by energy consumption per unit electricity production. Domestic water abstractions for the year 2000 were obtained from the FAO AQUASTAT database and *Gleick et al*. [2009]. Water use intensities were multiplied with domestic withdrawal in the year 2000 to account for economic development. Domestic water demand was approximated by multiplying population numbers per 0.5° x 0.5° cell from the FAOSTAT with country-specific domestic per capita water abstractions Daily fluctuations of domestic water demand were estimated based on daily air temperature.

Routing was performed along the river network based on the Simulated Topological Networks (STN30) [*Vörösmarty et al.*, 2000a]. The Global Reservoir and Dam database (GRanD) [*Lehner et al.*, 2011]) was used to represent reservoirs located on the drainage or river network.

Data on desalinated water abstractions were assumed constant over the year, and were taken from the FAO AQUASTAT database and from the WRI EarthTrends [http://www.wri.org/project/earthtrends/; *WRI*, 1998]. Assuming desalinated water is used close to where it is extracted, statistics of desalinated water use per country were spatially downscaled onto a global coastal ribbon of 40 km based on gridded population intensities.

If some of the demand cannot be satisfied from accessible blue water resources, the unmet demand is assumed satisfied with non-renewable groundwater abstractions.

For an extensive description of the PCR-GLOBWB model and for details of the preparation of industrial and domestic demand data, we refer to *Van Beek et al*. [2011], *Wada et al*. [2011a,b], *De Graaf et al*. [2014], and *Wada et al*. [2014].

4.2 Inclusion of irrigation efficiency

In this study, the actual amount of water that has to be abstracted from water resources for irrigation purposes (i.e., gross irrigation water requirements) was computed by multiplying net irrigation water requirements (i.e., crop-specific transpiration calculated as the difference between actual and potential evapotranspiration over irrigated areas) with irrigation systems project efficiencies per country around the year 2000. This approach has been successfully applied in previous studies (e.g., *Döll et al*. [2012], *Döll and Siebert* [2002], *Rost et al*. [2008], *Wisser et al*. [2010], *Wada et al*. [2011b]). Project irrigation efficiency around the year 2000 was retrieved from the country values data set compiled by *Rohwer et al*. [2007]. This database is shown in Figure 4-1. It presents more spatial detail than the regionally averaged irrigation water use efficiencies data set of *Döll and Siebert* [2002]. Irrigation water use efficiencies for the past and the future are discussed in the section 5.

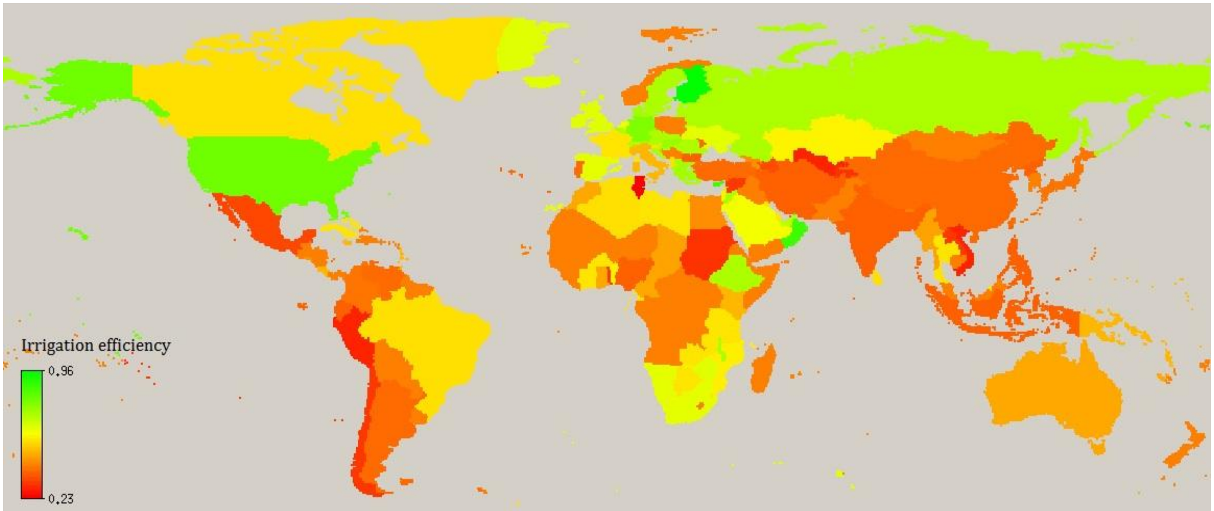

Figure 4-1: Global map of country specific irrigation efficiency. Adapted from *Rohwer et al*. [2007].

4.3 Data requirements and availability

4.3.1 Meteorological input

Monthly observations on climate variations over the 20th century until present conditions (i.e., January 1901-December 2012) are obtained from the Climatic Research Unit (CRU) Time-Series (TS) 3.21 data set of the University of East Anglia [*Jones and Harris*, 2013]. This data set is available from the British Atmospheric Data Centre (BADC) Archive (http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts/cru_ts_3.21/data/). It provides information at a spatial resolution of 0.5 × 0.5 ° on cloud cover, diurnal temperature range, frost day frequency, potential evapotranspiration, precipitation, daily mean temperature, monthly average daily maximum and minimum temperature, vapour pressure, and wet-day frequency. CRU TS 3.21 has the advantage to be based on observations and to cover the global land surface (excluding Antarctica). This data set relies on an archive of monthly observational data of average daily maximum and minimum temperatures provided by more than 4000 meteorological stations distributed across the world [*Jones and Harris*, 2013]. The CRU TS 3.21 data set is an updated version of CRU TS 3.10 [*Harris et al.*, 2013] that extends the data set coverage with year 2012 climatic data and corrects for errors. CRU TS 3.10 covers the period 1901-2009 and extends the coverage of CRU TS 2.1 (1901-2002) [*Mitchell and Jones*, 2005], which is an updated version of the earlier CRU TS 1.0 data set (1901-1995) [*New et al.*, 1999]. CRU TS 3.21 data set contains the primary variables directly obtained from station observations (i.e., mean temperature, diurnal temperature range, precipitation, wet-day frequency, vapour pressure and cloud cover), and the secondary variables derived from the primary ones (i.e., maximum and minimum arithmetical temperatures, frost day frequency, and potential evapotranspiration.

To account for climate variability, climate data of the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis [*Dee et al.*, 2011] is obtained from the National Center for Atmospheric Research (NCAR) data center (http://data-portal.ecmwf.int/data/d/interim_full_daily). Initiated in 2006, ERA-Interim was planned as an interim reanalysis in preparation for the next extended reanalysis to replace the earlier ERA-40 reanalysis [*Kållberg et al.*, 2005; *Uppala et al.*, 2005]. ERA-Interim reanalysis was elaborated to eliminate or reduce errors of ERA-40 (e.g., too-strong precipitation over oceans throughout the 1990s). ERA-Interim is a reanalysis of the global climate since 1989 and is extended in close to real time (December 2014) in a mode known as ECMWF Climate Data Assimilation System (ECDAS), until superseded by a new reanalysis (climate reanalysis over the period 1979-1988 was added in 2011). The ERA-Interim Archive is updated on a monthly basis. Its data assimilation and forecast system produces 4 analyses per day (i.e., every six hours, at 00, 06, 12, and 18 UTC) and 2 10-day forecasts per day, initialized at 00 and 12 UTC from the analyses. Gridded data products of ERA-Interim reanalysis include 3-hourly surface parameters: weather variables (e.g., surface air temperature, maximum and minimum temperature, humidity, and precipitable water), ocean-wave and land-surface conditions (e.g., surface sensible and latent heat fluxes), and 6-hourly upper-air parameters of the troposphere and stratosphere climate [*Simmons et al.*, 2007; *Berrisford et al.*, 2009; *Dee et al.*, 2011].

In this study, climatic conditions for the historical period 1960-2010 were simulated with the PCR-GLOBWB model using climate drivers (i.e., precipitation, temperature, and potential evapotranspiration) from the CRU TS 3.21 monthly data set, which was downscaled to daily values with the ERA-40 reanalysis. Reference potential evapotranspiration was calculated using the Penman-Monteith formula according to FAO guidelines [*Allen et al*., 1998]. For compatibility, climate data from the ERA-Interim reanalysis was bias-corrected by scaling the long-term monthly means of precipitation, temperature, and potential evaporation fields to those of the CRU TS 3.21 data set for the overlapping period, i.e., 1979-2010.

In addition to past and present climate conditions, future climate projections of the coupled model intercomparison project phase 5 (CMIP5) [*Taylor et al*., 2009, 2012] are obtained through the inter-sectoral impact model intercomparison project (ISI-MIP) [*Warszawski et al*., 2014]. Regular international projects have been organized since the beginning of the 21st century to intercompare the output of these models, assess climate models uncertainty, and understand what factors are responsible for the differences between climate projections [*Meehl et al*., 2000, 2005, 2007]. Model results of the CMIP3 were made publicly available and provided important inputs for numerous studies, as well as for the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report [*Solomon et al*., 2007; *IPCC*, 2007]. The new CMIP5 is the basis for future climate change projections of the recent IPCC fifth assessment report [*IPCC*, 2014]. It is a standard experimental protocol for studying the output of coupled ocean-atmosphere general circulation models. It organizes climate projections from numerous global climate models, allows for model intercomparison, and quantification of the uncertainties arising from the use of climate models and emission scenarios [*Osborne et al*., 2013; *Wada et al.*, 2013c]. Focused on the climate impact in different sectors (i.e., water, biomes, agriculture, health, and coastal infrastructure) at different scales (i.e., regional and global cross-scale assessment), the ISI-MIP enables quantifying the climate change impact at several global warming degrees and the uncertainty arising from the use of climate and impact models. The ISI-MIP climate data set covers the period 1960-2099 at a horizontal resolution of 0.5°. It consists of a common set of climate input, modeling protocol and central archive collecting output data made available to the wider research community for further analysis. Results from the CMIP5 are available at http://cmip.llnl.gov/cmip5/publications/ and through the Earth System Grid – Center for Enabling Technologies (ESG-CET) portal (http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html). ISI-MIP data is available at http://www.isi-mip.org.

In this study, the PCR-GLOBWB model was forced over the period 2006-2099 with climate projections of the CMIP5 taken from three global circulation models (GCMs), and one emission scenario (representative concentration pathway, RCP) from the ISI-MIP. The GCMs used are the HadGEM2-ES from the Met Office Hadley Centre [*Jones et al*., 2011], the IPSL-CM5A-LR from the Institute Pierre-Simon Laplace [*Dufresne et al*., 2013], and the GFDL-ESM2M [*Dunne et al*., 2012, 2013]. These projections are simulated under the RCP6.0, described as the ‘middle of the road’ (~ business as usual) scenario under the shared socioeconomic pathway SSP2 by *Wada and Bierkens* [2014] that corresponds to a global warming of ~ 4 °C by 2100. Reference potential evapotranspiration over the period 2006-2099 was computed using the Hamon relationship [*Hamon*, 1963] as a function of daily mean air temperature and the length of the day.

4.3.2 Irrigated areas data sets

The computation of irrigation water demand requires information on the extent of (actually) irrigated areas, cropping periods and patterns, crop water requirements and the type of crops cultivated. Over the last two decades, a number of global irrigated area data sets have been developed, using crop models, satellite imagery, and spatial unit statistics. Generally, global cropland extent or global area equipped for irrigation data sets were the result of the combination of statistics related to total cultivated and irrigated areas per spatial statistical unit (i.e., country, state) with satellite imagery or crop models [*Döll and Siebert*, 2000, 2005, 2007; *Heistermann*, 2006; *Freydank and Siebert*, 2008; *Ramankutty et al.*, 2008]. Until the development of the global data set of monthly irrigated and rainfed crop areas around the year 2000 (MIRCA2000) [*Portmann et al*., 2010], irrigated and rainfed areas have rarely been considered separately, and multicropping patterns were rarely included in global agricultural area data sets as well. Exceptions are, for example, *Bondeau et al*. [2007] that considered rice multicropping in Asia and *Rost et al.* [2008] that accounted for the additional supply of irrigation blue water over irrigation equipped areas when rainfall was insufficient to sustain the optimal growth of different crop classes.

The MIRCA2000 data set, used in this study, provides information on the growing areas of 26 crop classes (i.e., cotton, all major food crops, perennial, annual and fodder crops) for the period 1998-2002, explicitly including multicropping systems (i.e., when a crop is grown more than once a year over the same area). This data set consists of four different core products which are available for download at http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html: (i) monthly growing area grids for each of the 26 irrigated and rainfed crops at 5 arc min grid-cell resolution, (ii) condensed crop calendars for irrigated and rainfed crops (i.e., harvested area, start, and end of cropping periods) within each of the 402 spatial units considered, (iii) cropping period lists for irrigated and rainfed crops (i.e., harvested area, start, and end of cropping periods) at 5 arc min grid-cell resolution globally, and (iv) maximum monthly growing area grids for each of the 26 irrigated and rainfed crops at 5 arc min grid-cell resolution. Here, the 26 crop classes considered in the MIRCA2000 data set were aggregated into paddy and non-paddy groups, because paddy fields are generally subject to irrigation by flooding. Other data sets representing irrigated areas around the year 2000 exist: the global map of irrigated areas (GMIA) from the FAO/University of Frankfurt [*Siebert et al*., 2000, 2005, 2007, 2013], and the global irrigated area map (GIAM) data set from the IWMI [*Thenkabail et al*. 2006], available at http://www.iwmigiam.org. These data sets report areas equipped for irrigation at 5 arc min resolution and actual irrigated areas at 1 km grid-cell global resolution, respectively.

The global crop water model (GCWM) data set [*Siebert and Döll*, 2010] provides growing season lengths and crop factors representative for the year 2000. This information can be combined with the MIRCA2000 data set and used as model input to compute actual evapotranspiration, or green water availability [*Wada et al*., 2012a].

5. Model simulation

For each climate forcing data set (i.e., CRU TS 3.21, HadGEM2-ES, and IPSL-CM5A-LR), two model runs over both study periods (i.e., historical period 1960-2010 and future period 2006-2099) were formulated: no abstractions (i.e., natural climate variability only), and human-induced change (i.e., human activities abstractions and reservoir operations). Using climate forcing simulated under the RCP6.0 from the two GCMs HadGEM2-ES and IPSL-CM5A-LR, two projections of future water availability were made (i.e., 2 GCMs × 1 RCP). In order to reflect climate conditions prior to the start of the simulation period, each model run is simulated with a 30 years spin-up. Table 5.1 presents the general PCR-GLOBWB model simulation settings. One additional run was set up, where the climate conditions were kept fixed in order to assess the effects of irrigation efficiency independently of climate conditions. The model was run over the periods 2010-2060 and 2060-2099 with climate conditions from the CRU TS 3.21 data set repeated over both periods, and each variable was initialized with the states reported at the end of the previous period.

Table 5-1: Simulation settings.

	Period	Non-meteorological variables	Emission scenario	Climate forcing
Historical-Natural	1960-2010	See Historical of Table 5.2	RCP6.0	CRU TS 3.21
Historical-Human	1960-2010	See Historical of Table 5.2	RCP6.0	CRU TS 3.21
Future-Natural	2006-2099	See Future of Table 5.2	RCP6.0	HadGEM2-ES & IPSL-CM5A-LR
Future-Human	2006-2099	See Future of Table 5.2	RCP6.0	HadGEM2-ES & IPSL-CM5A-LR

The objective is to evaluate the impact of human water abstractions, primarily for irrigation purposes, in relation to improving irrigation efficiency. Hence, the amount of irrigation requirements satisfied is estimated by comparing simulated water availability with simulated gross irrigation water requirements, including irrigation water efficiencies. The human impact on water resources is evaluated by looking at global and regional river discharges. Therefore, changes in surface water and groundwater resources availability are evaluated in four selected river basins: the Indus, Mekong, Yellow River, and Mississippi river basins.

Irrigated areas grew from 53.3 million ha in 1900 to ~ 285 million ha (2.85 million km²) in 2003 [*Siebert et al.*, 2005, 2007; *Freydank and Siebert*, 2008; *Portmann et al.*, 2010]. Due to the little amount of data available on future projections of land use patterns, the contemporary extent of irrigated areas is kept constant (i.e., 2010's irrigated area extent), similarly to the study of *Wada and Bierkens* [2014]. Furthermore, irrigated areas are not expected to increase significantly in the next few decades, due to limitations in land and water availability [*Faures et al.*, 2002; *Bruinsma*, 2003; *FAO*, 2006a; *Alexandratos and Bruinsma*, 2012]. Hence, future water availability and abstractions only depict projected climate change (i.e., changing precipitation patterns, and global warming target of ~ 4 °C by 2100 based on the RCP6.0).

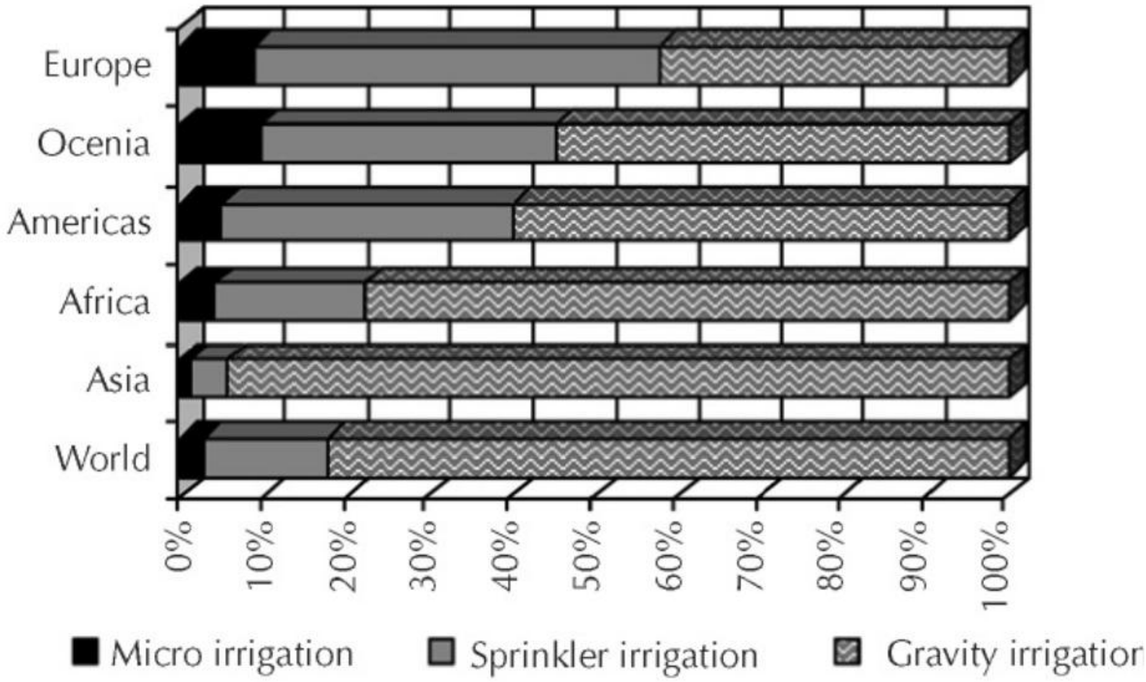

Figure 5-1: Proportion of irrigation types at the global and continental scale. From *Kulkarni et al*. [2006].

The large-scale use of sprinkler and drip irrigation started during the 1950's and the 1970's, respectively. [*Keller*, 2002; *Kulkarni et al*., 2006]. The number of countries with irrigated areas equipped for micro-irrigation has more than doubled over the past two decades [*Kulkarni et al*., 2006]. Micro-irrigated area expanded from 0.41 million ha to 1.77 million ha in 1991 [International Commission on Irrigation and Drainage (ICID), 1993] and to ~ 3.0 million ha in 2000 [*Reinders*, 2000]. The proportion of surface irrigation, sprinkler irrigation, and micro-irrigation, as estimated by *Kulkarni et al*. [2006], is presented in the figure 5.1.

Few studies have provided information on future irrigation efficiency. *Bruinsma* [2003] developed a function to evaluate irrigation efficiency improvements towards 2030 in developing countries by accounting for irrigation water use efficiencies over the period 1997-1999 and regional water scarcity, implying the lack of water resources as a driver for irrigation efficiency improvement. *Bruinsma* [2003] reported an improvement of irrigation efficiency in developing countries of 4%, from ~ 0.38 (1997-1999) to ~ 0.42 (2030), which is equivalent to an annual improvement rate of 0.3 % yr^{-1}. *Alcamo et al*. [2005] reported a global rate of irrigation efficiency improvement ranging from 0.15 % yr^{-1} to 1.2 % yr^{-1} towards 2050, based on the ecosystems and human society development described in the millennium ecosystem assessment scenarios. *Hanasaki et al*. [2013] combined high improvement rates (i.e., 0.30 % yr^{-1}) of irrigation efficiency with shared socioeconomic pathways SSP1 and SSP5, medium rate with SSP2 (i.e., 0.15 % yr^{-1}), and low rate (i.e., 0.0 % yr^{-1}) for SSP3.

In this study, we used *Fischer et al*.'s [2007] simple assumptions on the rate of increase of irrigation efficiency, based on global irrigation water use efficiencies around the index year 2000 reported by *Rohwer et al*. [2007]. Over the period 1960-1970, irrigation efficiency is assumed to be constant at 90 % of values for the index year 2000, and is assumed to reach values reported by *Rohwer et al*. [2007] at the end of the period 1970-2000. Gross irrigation water requirements are computed for the period 2000-2030 by assuming an irrigation efficiency increase over that period of 10 %, and a further 10 % increase is assumed from

2030 to 2080. Finally, irrigation efficiency is assumed to remain constant over the period 2080-2099. Upper boundary of irrigation efficiency is set to 0.9 over the complete study period, which corresponds to micro-irrigation field application efficiency [*Rohwer et al.*, 2007]. Table 5.2 provides the sources of non-meteorological variables, among which the sources and the development of irrigation efficiency over time, presented in the figure 5.2.

Table 5-2: Non-meteorological variables.

Variable	Historical (1960-2010)	Future (2006-2099)	
Crop coefficient & max. rooting depth	Siebert and Döll [2010]	Siebert and Döll [2010]	
Irrigated area	FAOSTAT & Portmann et al. [2010]	Fixed at 2010's irrigated area extent	
Crop classes	Portmann et al. [2010]	Portmann et al. [2010]	
Irrigation efficiency	1960-1970: 90% of index year 2000; 1970-2010: + 0.33 % yr^{-1} based on index year 2000	2006-2030: + 0.33 % yr^{-1} based on index year 2000; 2030-2080: +0.2 % yr^{-1} based on index year 2000; 2080-2099: 120 % of index year 2000	Values for the index year 2000 are taken from Rohwer et al. [2007]; Irrigation efficiency improvement scenario is adapted from Fischer et al. [2007]
Large size reservoirs	Lehner et al. [2011]	Lehner et al. [2011]	

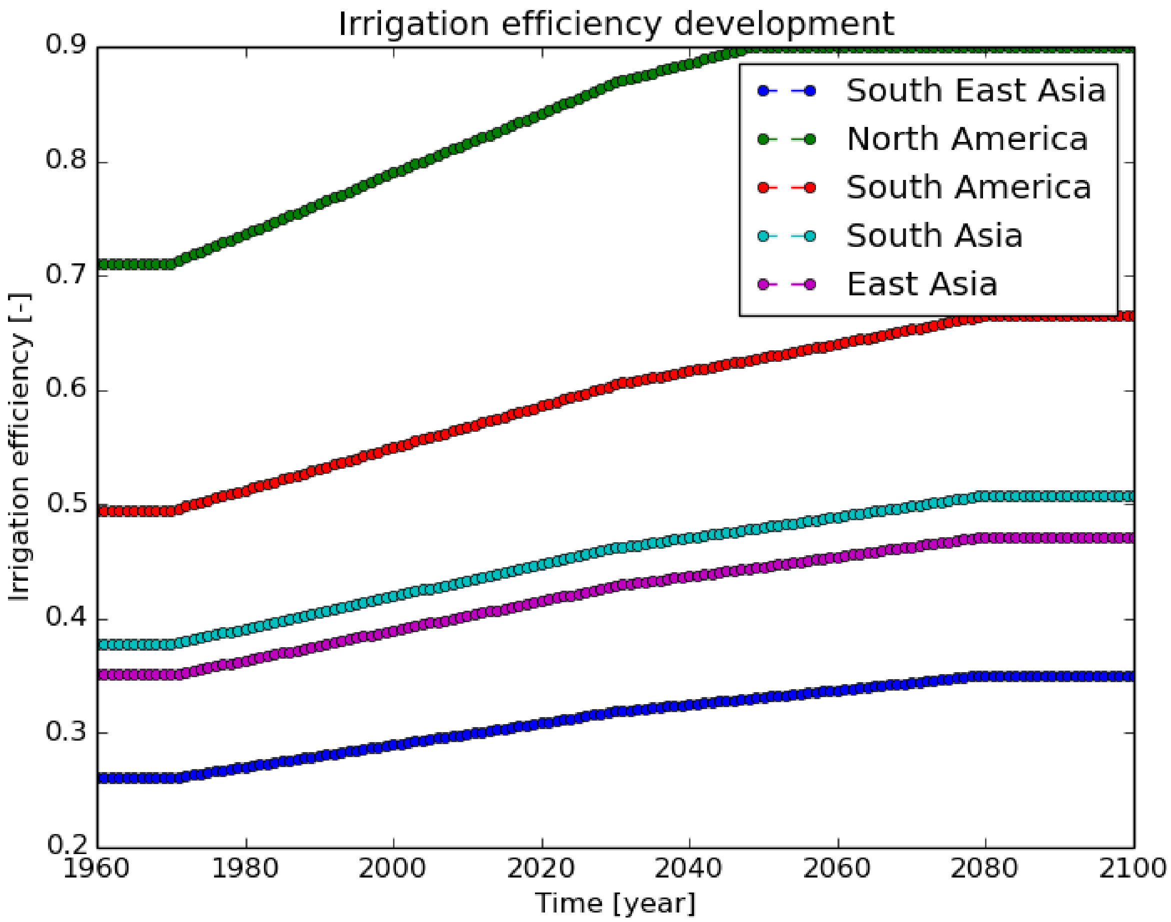

Figure 5-2: Irrigation efficiency development in five selected river basins (i.e., Indus, Mekong, Yellow River, Mississippi, and Amazon). Adapted from *Fischer et al*. [2007] and *Rohwer et al*. [2007].

6. Results

6.1 Model validation

The PCR-GLOBWB model and model outputs have been extensively validated in earlier work. In the study of *Van Beek et al*. [2011], simulated river discharge and simulated continental runoff were compared with observed values at yearly and monthly time scales using data from a selection of 2219 global runoff data centre (GRDC) stations [*GRDC*, 2008], and simulated evapotranspiration was validated against that of the ERA-40 reanalysis [*Kållberg et al*., 2005; *Uppala et al*., 2005]. Water stress over the period 1960-2000 was validated against estimates from previous studies (e.g., *Vörösmarty et al*. [2000], *Oki et al*. [2001], *Islam et al*. [2007], *Kummu et al*. [2010]), and gross sectoral and total water demand per country were compared to reported values from the FAO AQUASTAT database, from *Shiklomanov* [2000a, b] (total water demand), from *Steinfeld et al.* [2006] (livestock water demand), and from *Shen et al*. [2008] by *Wada et al*. [2011a]. *Wada et al*. [2011b] compared simulated irrigation water demand with estimates from previous studies (e.g., *Shiklomanov* [2000b], *Döll and Siebert* [2002], *Hanasaki et al*. [2006], *Rost et al*. [2008], *Wisser et al*. [2008]) while the sum of simulated livestock and irrigation water demand was compared to the annual agricultural water withdrawal per country as reported by the FAO AQUASTAT database. In addition, in this study, calculated water stress was compared to estimates from several other studies (e.g., *Revenga et al*. [2000], *Arnell* [2004], *Hanasaki et al*. [2008b]). Simulated terrestrial water storage was compared to the GRACE satellite observations for the period 2003-2008 [*Liu et al*., 2010], and simulated groundwater abstractions were compared with reported values from the USGS for the United States and with several independent non-renewable groundwater abstraction estimates (e.g., *Konikow* [2011]) by *Wada et al*. [2012a]. *Wada et al.* [2014] validated simulated water withdrawal per source against reported country and state values for the year 2005 at the global scale, for Europe, the USA, and for Mexico, and compared simulated terrestrial water storage anomalies with those of the GRACE satellite observations over the period 2003-2010. Finally, simulated total and groundwater abstractions were compared with reported FAO AQUASTAT data and results of *Wada et al*. [2012a], and simulated minimum monthly discharge was compared to observed values for the period 1960-2010 by *De Graaf et al*. [2014]. For an extensive description of the validation of the model PCR-GLOBWB and its outputs, we refer to *Van Beek et al*. [2011] and *Wada et al*. [2014]. PCR-GLOBWB model outputs generally show good agreement with observed values and estimates from other studies, apart from small errors like the slight under estimation of agricultural water abstractions in *Wada et al*. [2011b], primarily over countries with paddy irrigation and for which the application of an irrigation efficiency factor of 0.8 was certainly too optimistic.

6.2 Global observations

The figure 6.1 below shows annual precipitation rates over the globe for model simulations under natural or pristine conditions such that human activities impact on climate variables (e.g., evapotranspiration and transpiration) is not incorporated. Annual precipitation over the historical period (i.e., from the CRU TS 3.21 dataset) ranges from ~ 108000 km^3 yr^{-1} to ~ 116000 km^3 yr^{-1}, while average precipitation of the three GCM projections over the future study period 2006-2099 slightly increases from ~ 114000 km^3 yr^{-1} to ~ 116000 km^3 yr^{-1}. The tendency curve, and its equation and coefficient of determination displayed in figure 6.1 were derived from the average precipitation of all climate data sets used (i.e., CRU TS 3.21, HadGEM2-ES, IPSL-CM5A-LR, and GFDL-ESM2M).

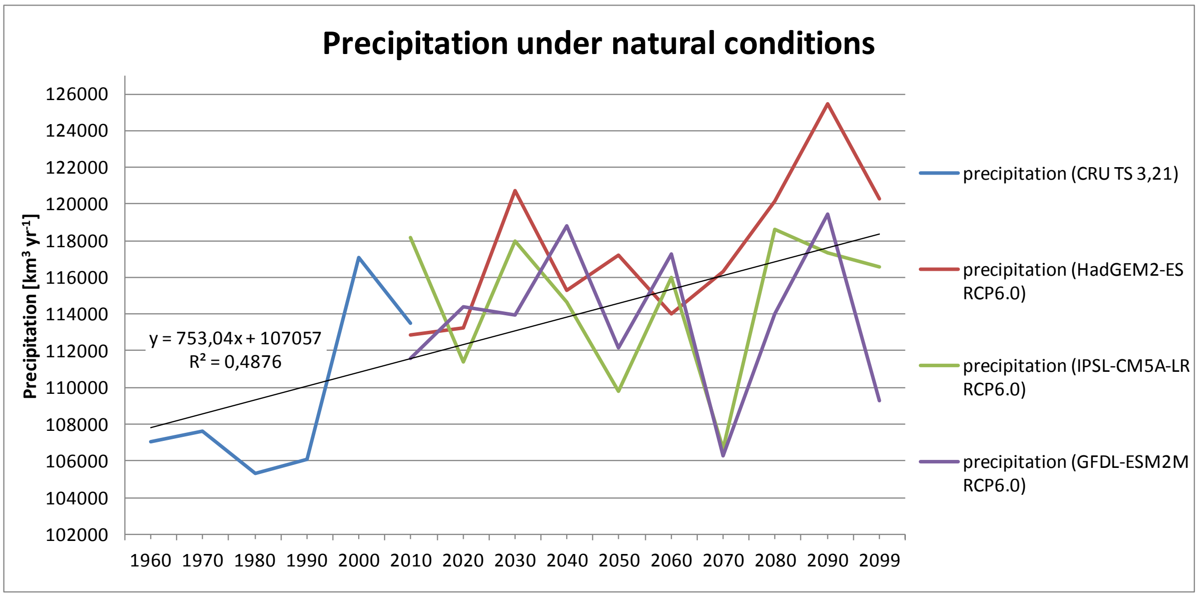

Figure 6-1: Global annual precipitation rates under natural conditions over the period 1960-2099.

Using the advanced visualization Aguila software included in the PCRaster Python distribution package, maps that represent model outputs are shown below.

It has to be stressed that during this study, errors have emerged from the latest release of the model PCR-GLOBWB, suggesting too much percolation loss to the groundwater. It resulted that abnormal high values for (gross) irrigation water demand were computed. Therefore, resulting figures may seem not realistic but are anyway presented in this section, in order to show the magnitude of the impact of irrigation activities and the effects of irrigation water use efficiencies improvement on irrigation water demand. To display correct patterns of gross irrigation water requirements, gross irrigation water demand is plotted on a semi-logarithmic scale with a maximum value set to 3 m yr^{-1}, considering lowest irrigation efficiency is ~ 1/3 and assuming that few or no crops transpire more than 1000 mm yr^{-1}.

In addition, it is important to notify that the global annual totals presented here correspond to the total irrigation water demand per calendar year, which may deviate substantially from the actual demand over the cropping season, with water abstractions more concentrated over crop growing periods and no irrigation water demand over the rest of the year.

The global gross irrigation water requirements for the year 1960 and for the year 2000 computed by the model under CRU TS 3.21 climate conditions are shown in the figure 6.2 and the figure 6.3, respectively. The global simulated gross irrigation water demand over the year 1960 is ~ 1850 km^3 yr^{-1}. It amounts to ~ 5660 km^3 yr^{-1} for the year 2000.

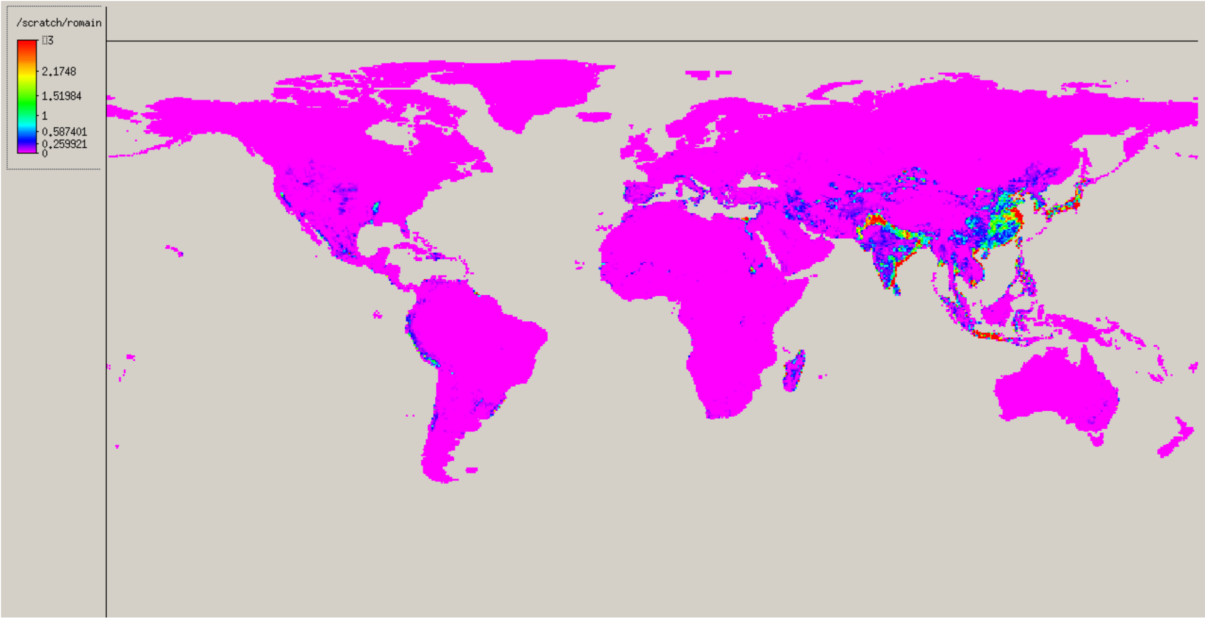

Figure 6-2: Simulated global gross irrigation water requirements for the year 1960 under CRU-TS 3.21 climate forcing.

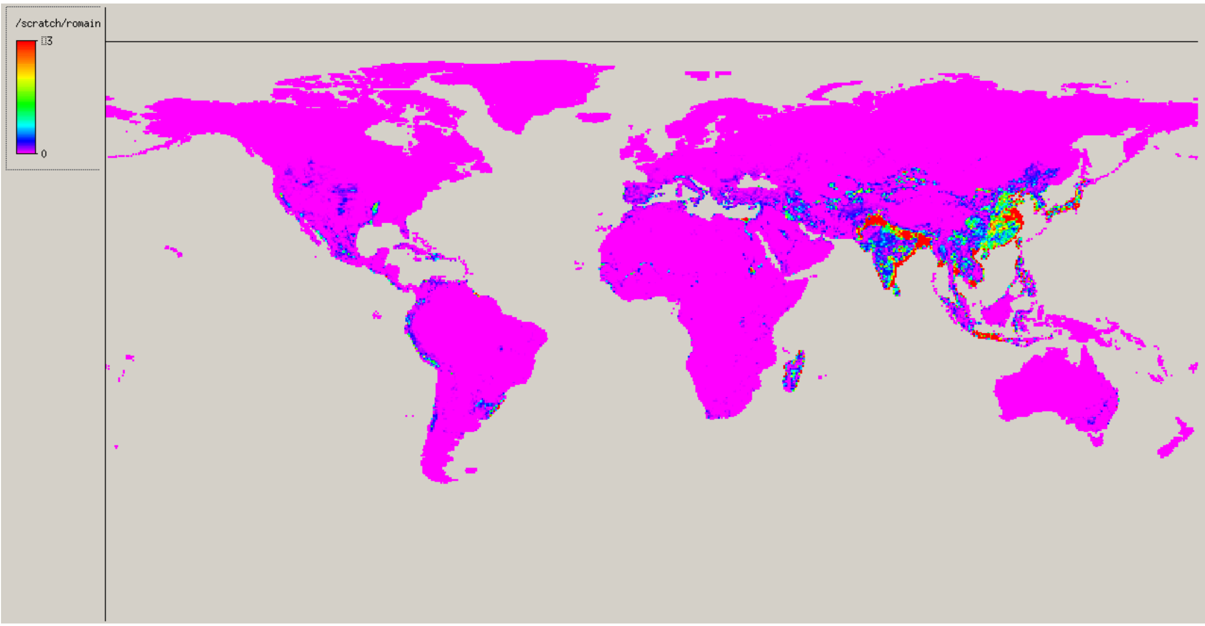

Figure 6-3: Simulated global gross irrigation water requirements for the year 2000 under CRU-TS3.21 climate forcing.

Over the period 1960-2010, large increases in gross irrigation water requirements are observed over major irrigated areas, that is, North eastern China, India, Japan, Indonesia, South central Asia, South central America, the Nile and Mississippi river basins, and around the Mediterranean basin.

The global gross irrigation water requirements for the year 2020 and for the year 2090 simulated under HadGEM2-ES climate conditions are shown in the figure 6.4 and the figure 6.5, respectively. Using climate variables from the HadGEM2-ES GCM projection, the

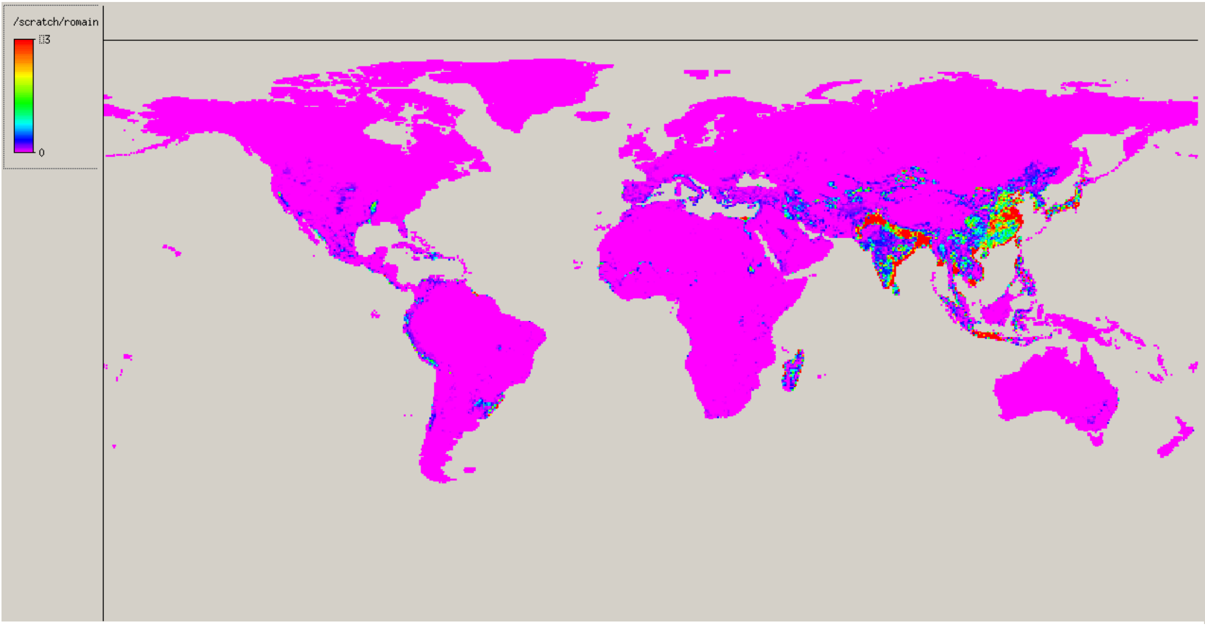

Figure 6-4: Simulated global gross irrigation water requirements for the year 2020 under HadGEM2-ES climate forcing.

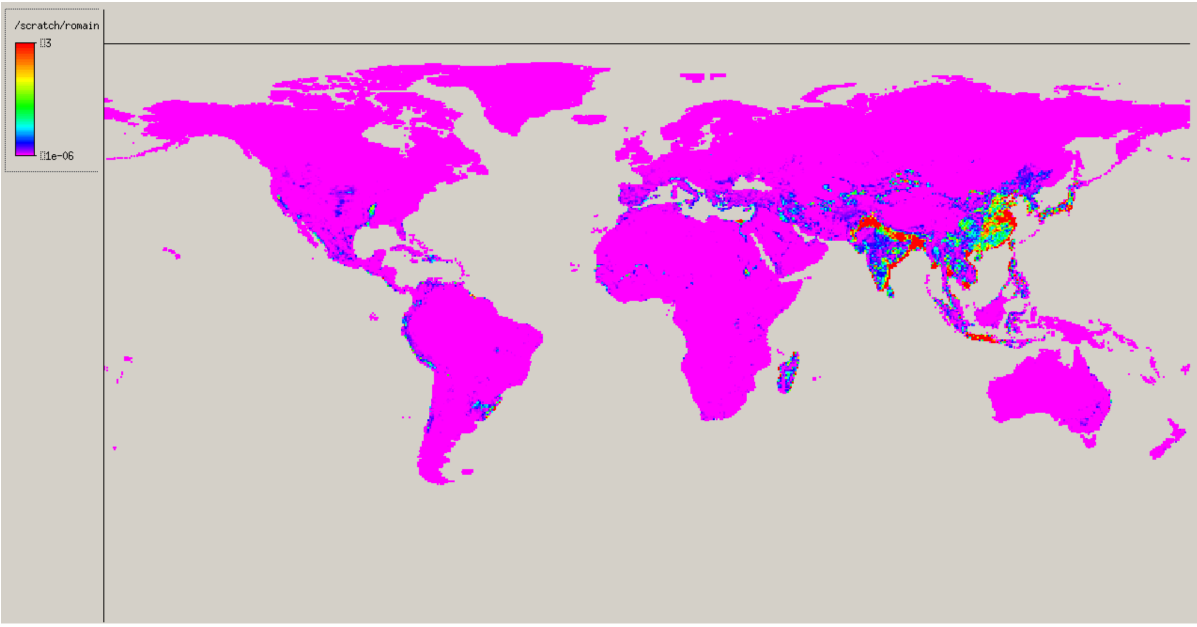

Figure 6-5: Simulated global gross irrigation water requirements for the year 2090 under HadGEM2-ES climate forcing.

global simulated gross irrigation water demand in 2020 is ~ 7060 km^3 yr^{-1} and ~ 6760 km^3 yr^{-1} over the year 2090.

Gross irrigation water requirements in 2020 are higher than those observed using climate variables from the CRU TS 3.21 dataset in 2000, and the most important increases from 2000 to 2020 occurred over the areas where large increases of irrigation water requirements took place during the historical period (e.g., North eastern China, India, South central Asia). A very slight decrease (~ 300 km^3 yr^{-1}) in gross irrigation water requirements is observed between 2020 and 2090, predominantly over major irrigated areas (e.g., the Indus, Brahmaputra, Ganges, Yellow River, and Nile river basins).

The global gross irrigation water requirements for the year 2020 and for the year 2090 simulated under IPSL-CM5A-LR climate conditions are shown in the figure 6.6 and the

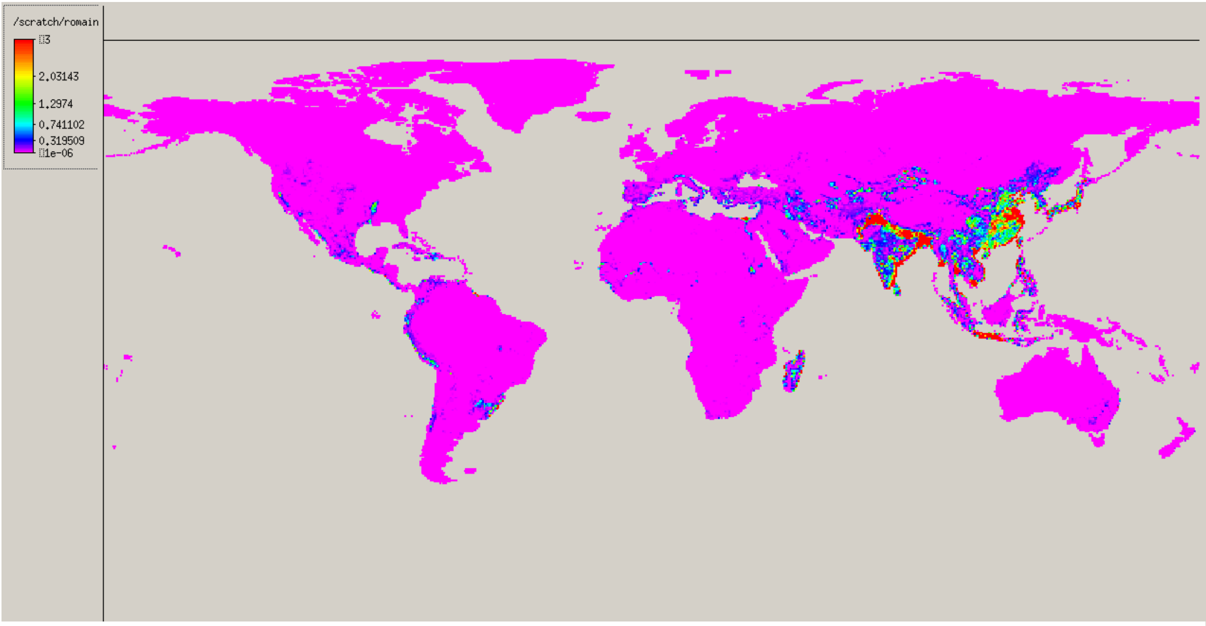

Figure 6-6: Simulated global gross irrigation water requirements for the year 2020 under IPSL-CM5A-LR climate forcing.

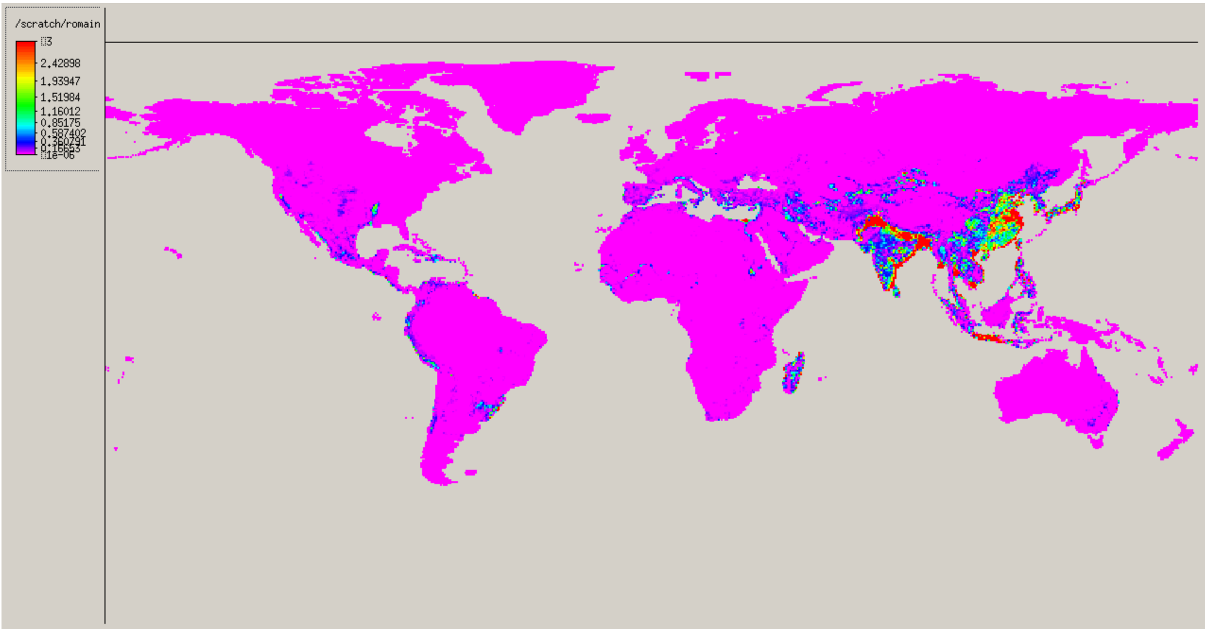

Figure 6-7: Simulated global gross irrigation water requirements for the year 2090 under IPSL-CM5A-LR climate forcing.

figure 6.7, respectively. Global simulated gross irrigation water demand over the year 2020 is ~ 7200 km^3 yr^{-1} and ~ 7030 km^3 yr^{-1} in 2090.

Gross irrigation water requirements in 2020 and in 2090 are higher than those simulated over the same years using climate variables from the HadGEM2-ES dataset. Similarly to model outputs simulated under HadGEM2-ES climate conditions, a slight decrease in gross irrigation water requirements (~ 175 km^3 yr^{-1}) is observed between 2020 and 2090, predominantly over major irrigated areas.

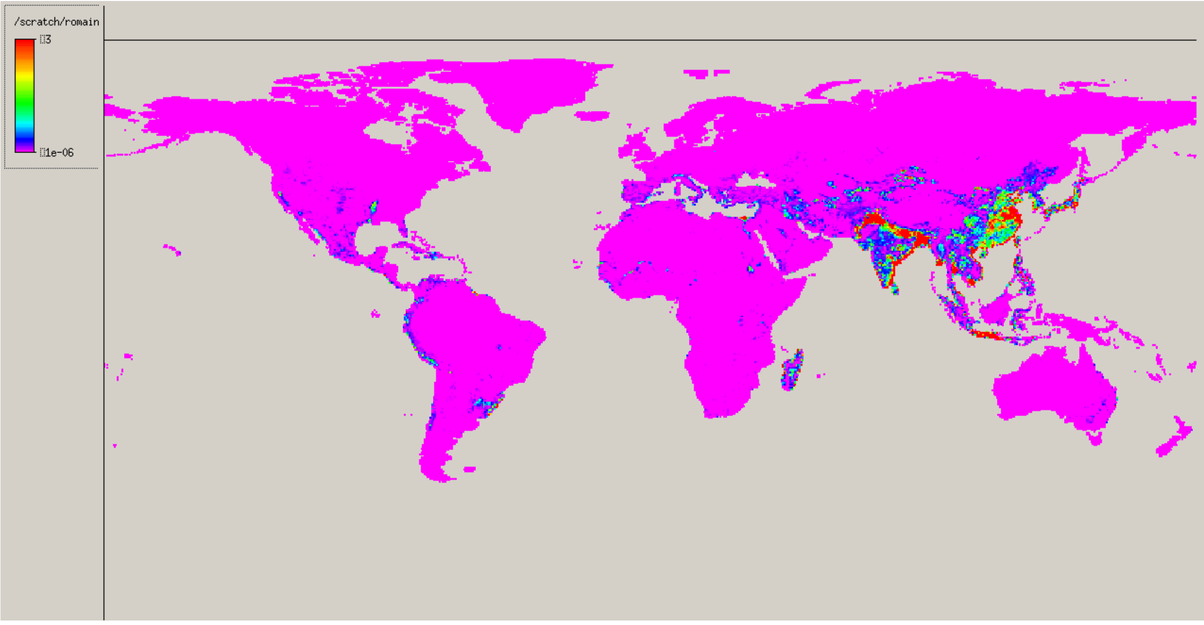

Figure 6-8: Simulated global gross irrigation water requirements for the year 2020 under GFDL-ESM2M climate forcing.

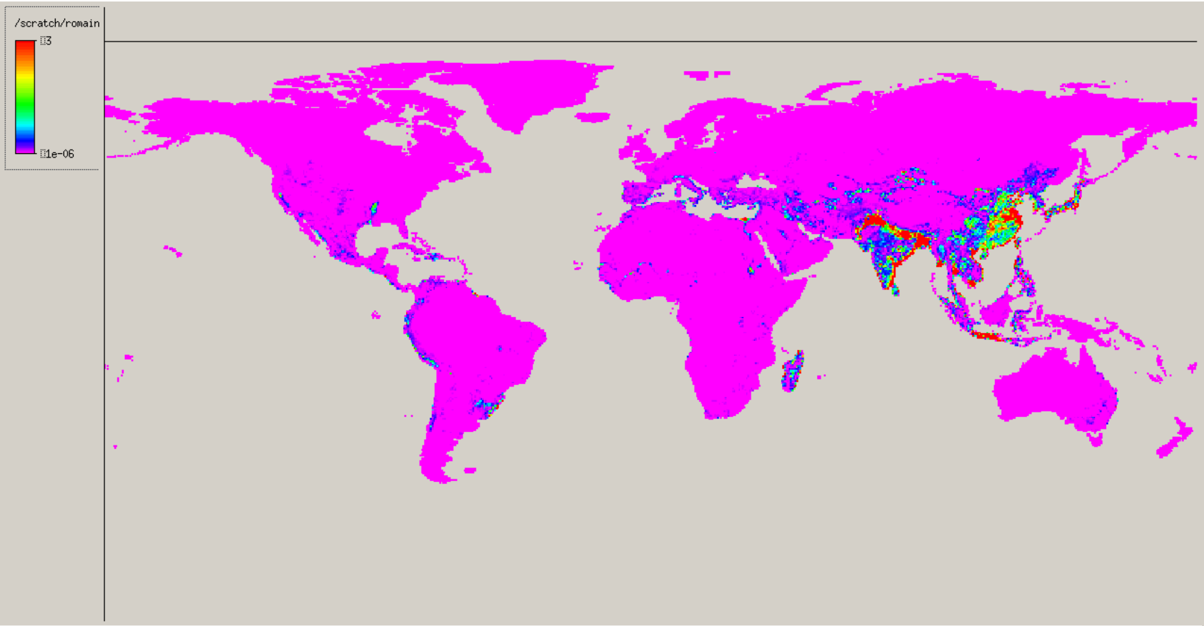

Figure 6-9: Simulated global gross irrigation water requirements for the year 2090 under GFDL-ESM2M climate forcing.

The global gross irrigation water requirements for the year 2020 and for the year 2090 simulated under GFDL-ESM2M climate conditions are shown in the figure 6.8 and the figure 6.9, respectively. Global simulated gross irrigation water demand over the year 2020 is ~ 7310 km^3 yr^{-1} and ~ 6750 km^3 yr^{-1} in 2090.

Gross irrigation water requirements in 2020 are higher than those simulated with IPSL-CM5A-LR and HadGEM2-ES, however gross irrigation water demand in 2090 simulated under GFDL-ESM2M climate forcing is the lowest. Hence, the decrease in simulated irrigation water requirements is the most important compared to the two other runs using GCMs projections, with a decrease in gross irrigation water demand of ~ 560 km^3 yr^{-1}.

Estimates of gross irrigation water requirements for the year 2020 and for the year 2090 simulated under continued CRU-TS 3.21 climate forcing over the period 2010-2099 are

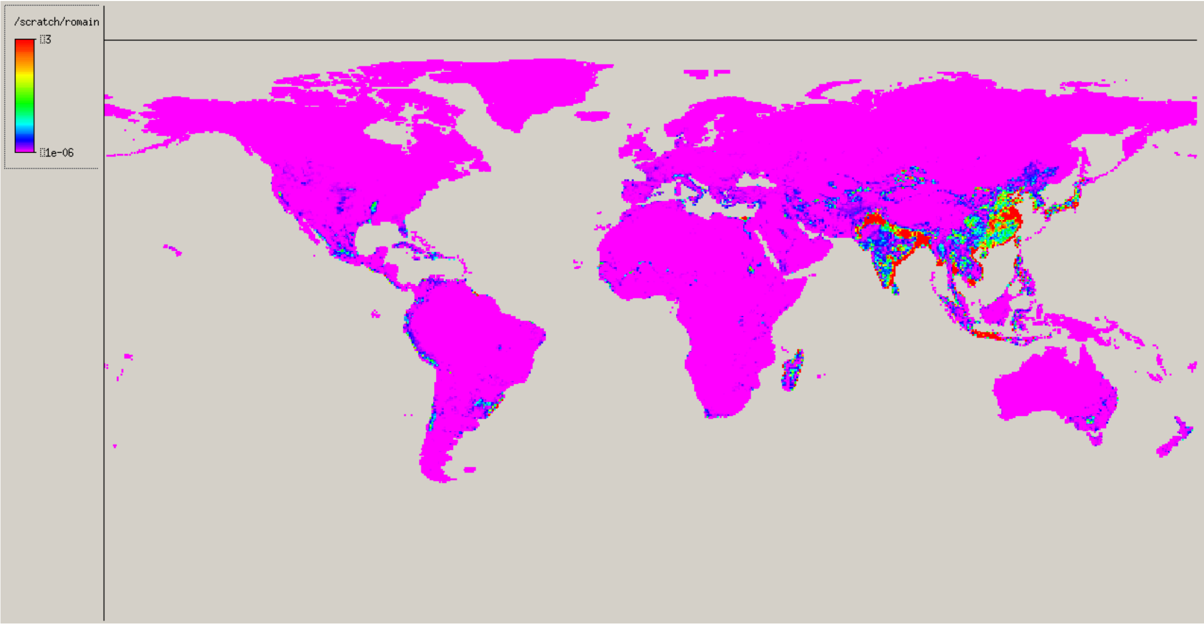

Figure 6-10: Simulated global gross irrigation water requirements for the year 2020 under continued CRU-TS 3.21 climate forcing.

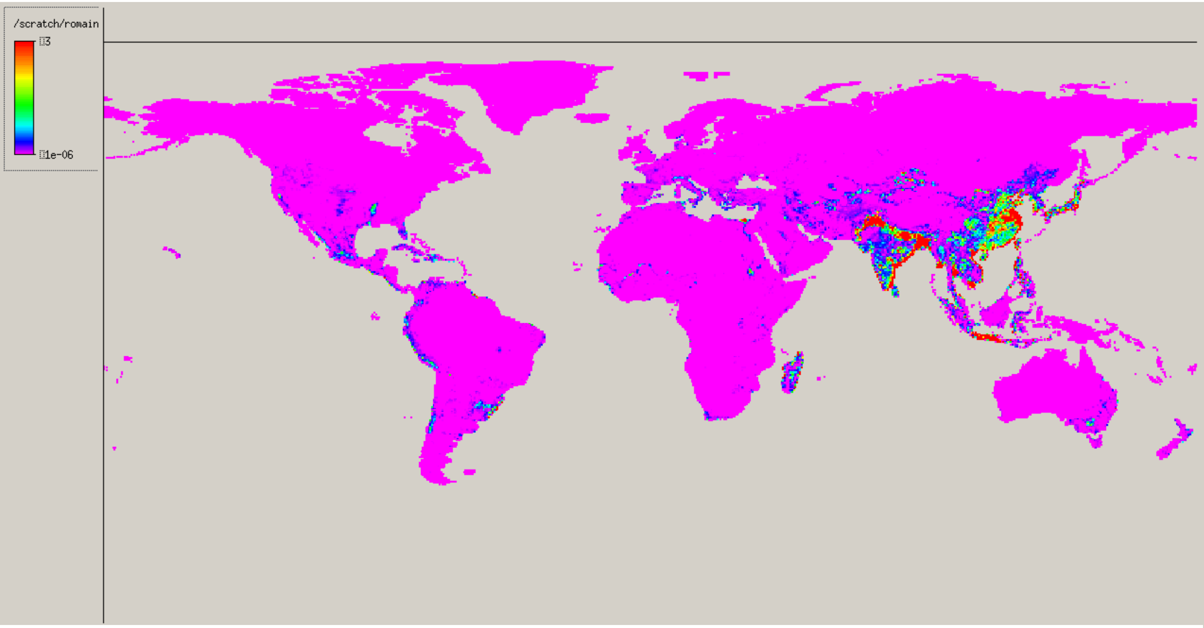

Figure 6-11: Simulated global gross irrigation water requirements for the year 2090 under continued CRU-TS 3.21 climate forcing.

shown in the figure 6.10 and in the figure 6.11, respectively. Global simulated gross irrigation water demand in 2020 is ~ 7555 km^3 yr^{-1} and ~ 6990 km^3 yr^{-1} in 2090.

The gross irrigation water demand in 2020 simulated with repeated climate conditions from the CRU-TS 3.21 climate dataset is the highest among all runs, yet irrigation water requirements simulated under the same conditions in 2090 compare well with the results from the three runs using GCMs climate input where global irrigation water requirements range from 6750 to 7030 km^3 yr^{-1}. In addition, the decrease in simulated gross irrigation water demand from 2020 to 2090 (~ 560 km^3 yr^{-1}) is similar to the decrease observed when the model is forced with GFDL-ESM2M climate input.

6.3 Regional observations

In addition to the global annual values of gross irrigation water requirements, maps of annual gross irrigation water demand per river basin plotted on a semi-logarithmic scale with a maximum value set to 3 m yr^{-1} are presented, using the Aguila visualization software.

Irrigation water requirements per cell were aggregated and averaged over the surface of river basins to obtain maps of total annual irrigation water demand per river basin. This allows highlighting the magnitude of the impact of irrigation activities over river basins.

Gross irrigation water requirements per basin for the year 1960 and 2000 using the CRU TS 3.21 dataset are presented in the figure 6.12 and the figure 6.13, respectively.

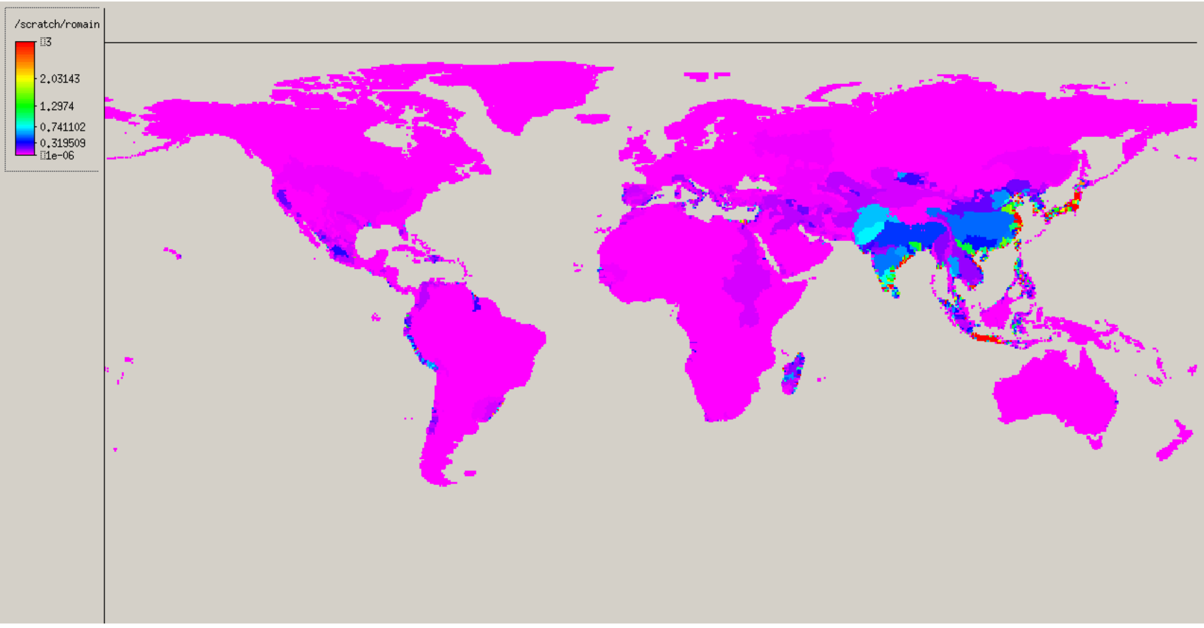

Figure 6-12: Simulated global gross irrigation water requirements per river basin for the year 1960 under CRU-TS 3.21 climate forcing.

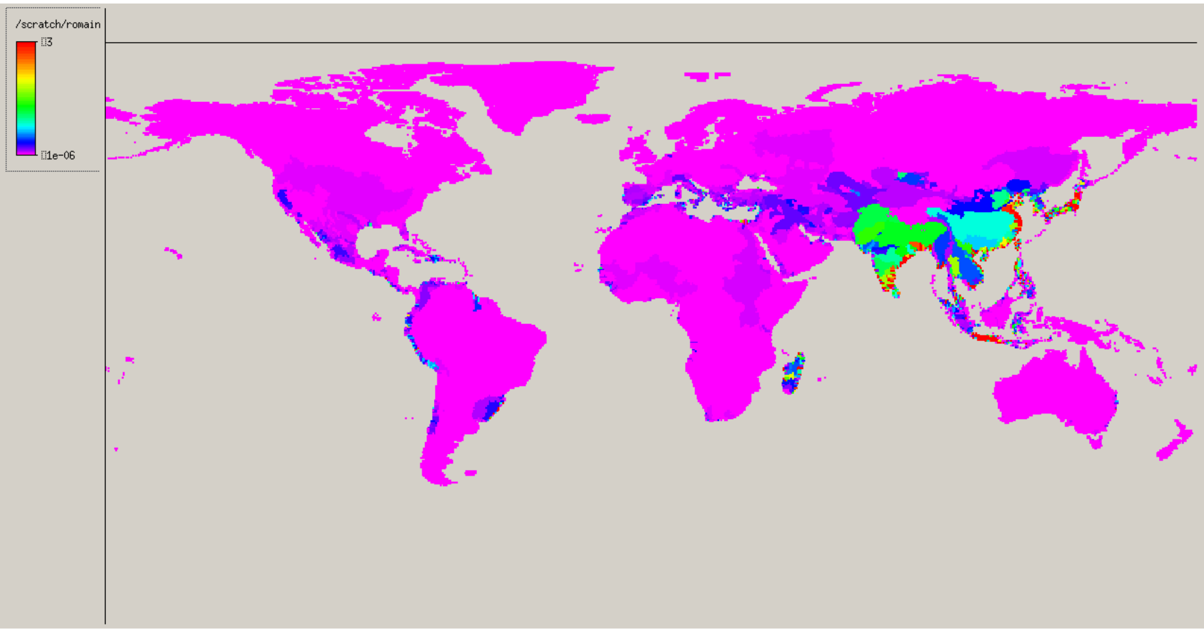

Figure 6-13: Simulated global gross irrigation water requirements per river basin for the year 2000 under CRU-TS 3.21 climate forcing.

Over the historical period 1960-2010, gross irrigation water demand significantly increased over heavily irrigated basins: it has nearly or more than doubled (from ~ 0.3 m yr^{-1} to ~ 0.6 m yr^{-1} or higher) over the Mississippi, Nile, Indus, Ganges, Brahmaputra, Mekong, Bengawan Solo, Yellow River, Yangtse, and Amur river basins. Over the same period, other regions have increasingly been subjected to irrigation water demand: Madagascar, South central and South western America, Central America, river basins located around the Mediterranean basin, especially in Spain and Tunisia, Middle East, and central Asia.

Gross irrigation water requirements per basin for the year 2020 and 2090 using the GFDL-ESM2M GCM climate projection are presented in the figure 6.14 and the figure 6.15, respectively.

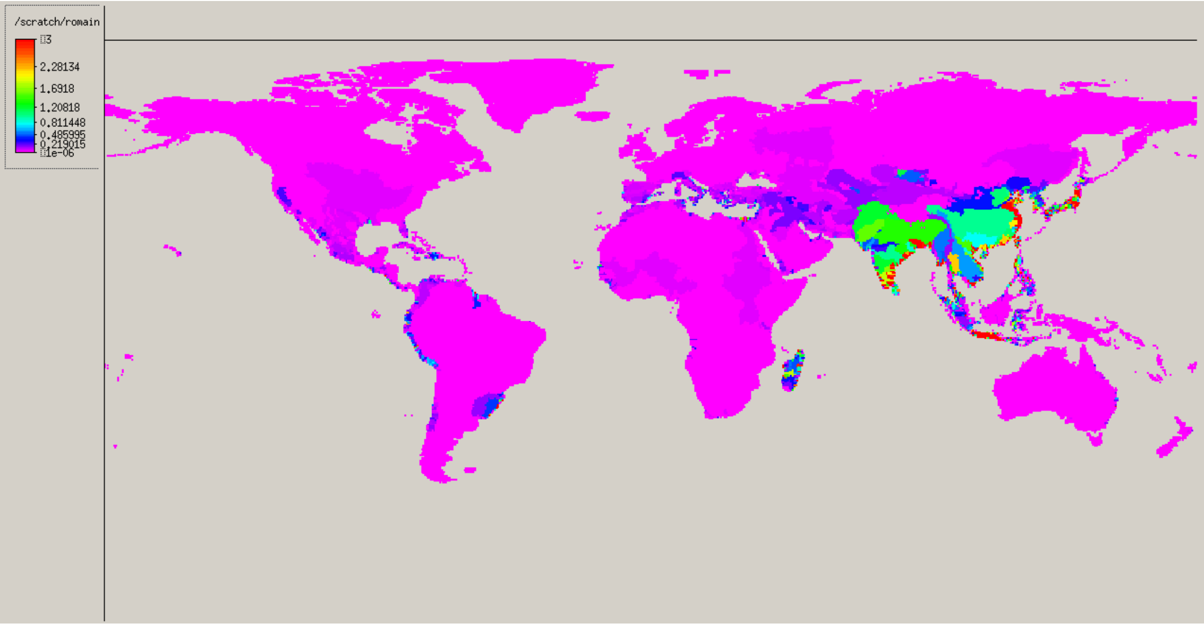

Figure 6-14: Simulated global gross irrigation water requirements per river basin for the year 2020 under GFDL-ESM2M climate forcing.

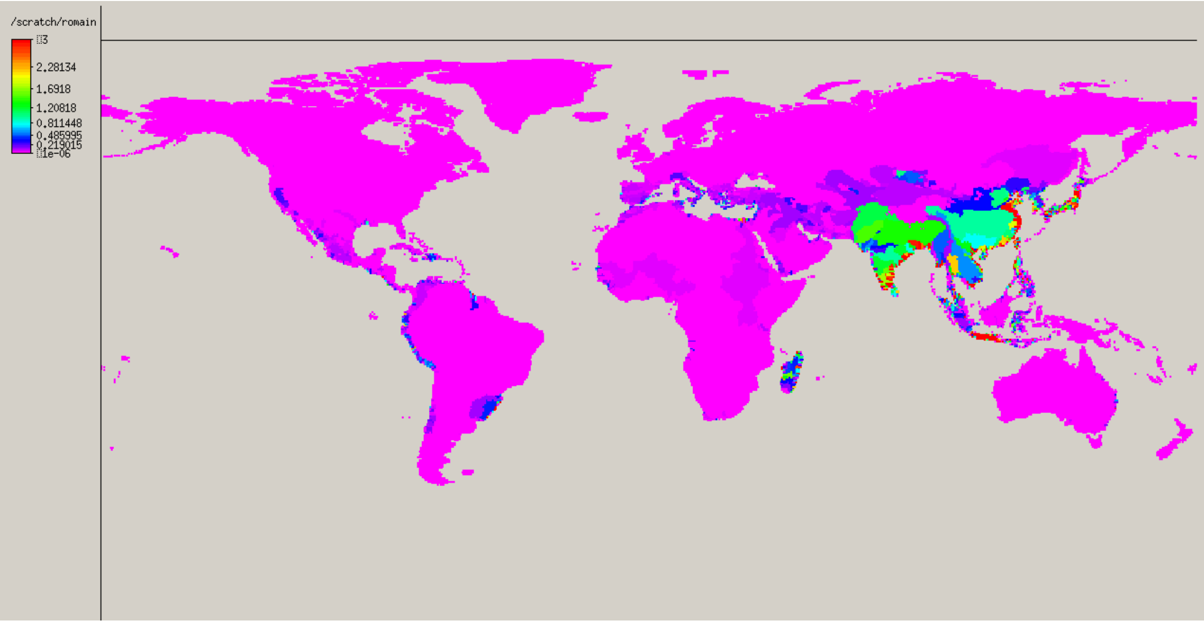

Figure 6-15: Simulated global gross irrigation water requirements per river basin for the year 2090 under GFDL-ESM2M climate forcing.

GFDL-ESM2M climate input was preferred to the other GCM climate projections at this step because projected precipitation lies between the precipitation rates simulated with the IPSL-CM5A-LR and the HadGEM2-ES.

In regions affected by irrigation activities, irrigation water requirements per basin are slightly lower in 2090 compared to the situation in 2020. However, over the North central America, some parts of Middle East, and Western Asia, irrigation water demand decreases over the next century so that it is almost becomes zero.

Finally, ratios of gross irrigation water demand per cell, per year over four locations relative to the gross irrigation water requirements for the year 2000 (for the historical period) and for the year 2020 (for the period 2006-2099) were computed. These locations correspond to the Mississippi (red marker), Indus (white marker), Yellow River (blue marker), and Mekong river basins (green marker). This selection is intended to assess irrigation efficiency improvement impact on irrigation water demand in areas of contrasting technological and economic development: traditional, low efficiency irrigation in the Indus river basin, highly efficiencient and mainly non-paddy irrigation in the Mississippi river basin, low efficiency, moonsoon-dependent paddy irrigation over the Mekong river basin, and moderately efficient irrigation in the Yellow River.

Ratios of gross irrigation water demand, computed with climate data from the CRU TS 3.21 dataset, over the four selected locations relative to the gross irrigation water requirements in 2000 are presented in the figure 6.16.

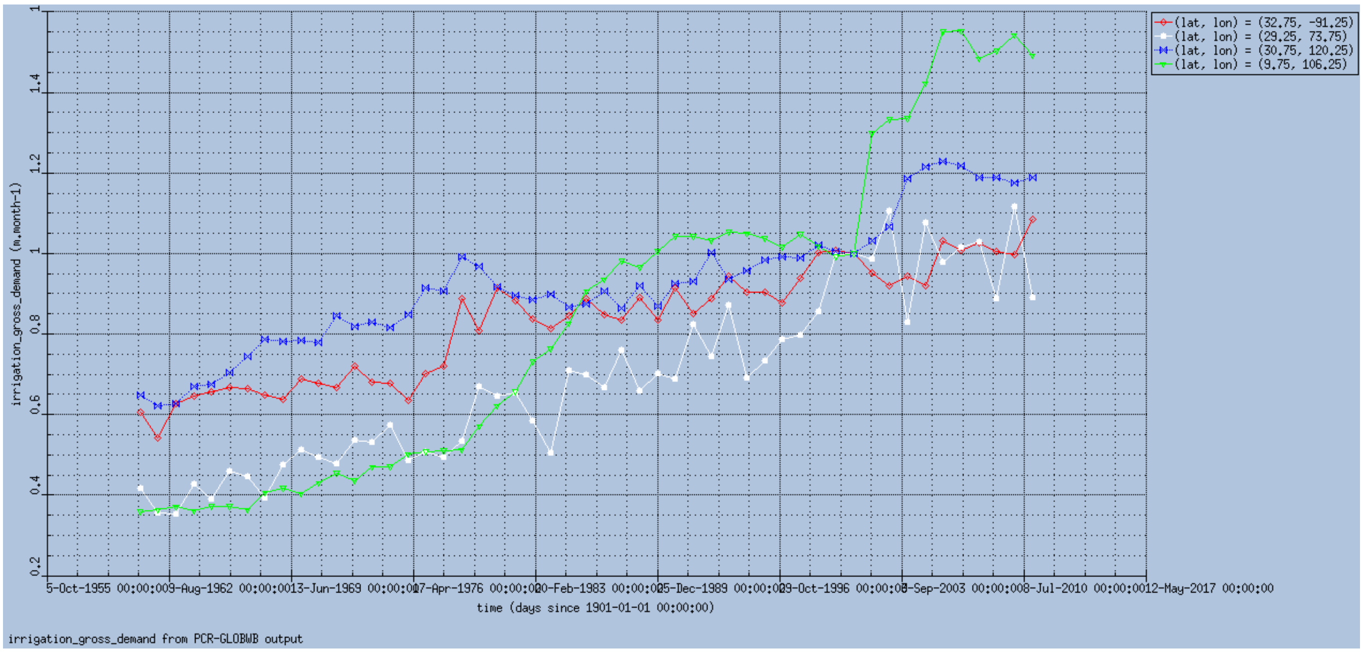

Figure 6-16: Ratios of gross irrigation water requirements in four locations relative to the gross irrigation water requirements in 2000. Gross irrigation water requirements are computed using CRU TS 3.21 climate forcing. The four locations correspond to the Mississippi (red), Indus (white), Yellow River (blue), and Mekong river basins (green).

Gross irrigation water requirements in 1960 in the Mississippi and Yellow river basins (red and blue markers) were ~ 60 % of those in 2000, while in the Indus and Mekong river basins (white and green markers), gross irrigation water requirements in 1960 amounted to ~ 40 % of what was required in 2000. All four river basins have registered a significant increase in gross irrigation water demand, however this increase was more important in the Mekong basin during the 1980s. After the year 2000 until the year 2010, gross irrigation water requirements in the Mississippi and Indus river basins remain in the same order of magnitude (~ 100% of their levels in 2000) while a significant increase of gross irrigation water requirements are observed in the Yellow river basin (~ + 20 %) and in the Mekong river basin (> + 40 %). Very large (or low) values in te time series of ratios may be due to the absence of irrigation activity from a year to another.

Ratios of gross irrigation water demand, computed for the period 2006-2099 with climate data from three GCM projections (i.e., HadGEM2-ES, IPSL-CM5A-LR, and GFDL-ESM2M), over the four selected locations relative to the gross irrigation water requirements in 2020 are presented in the figure 6.17, 6.18, and 6.19.

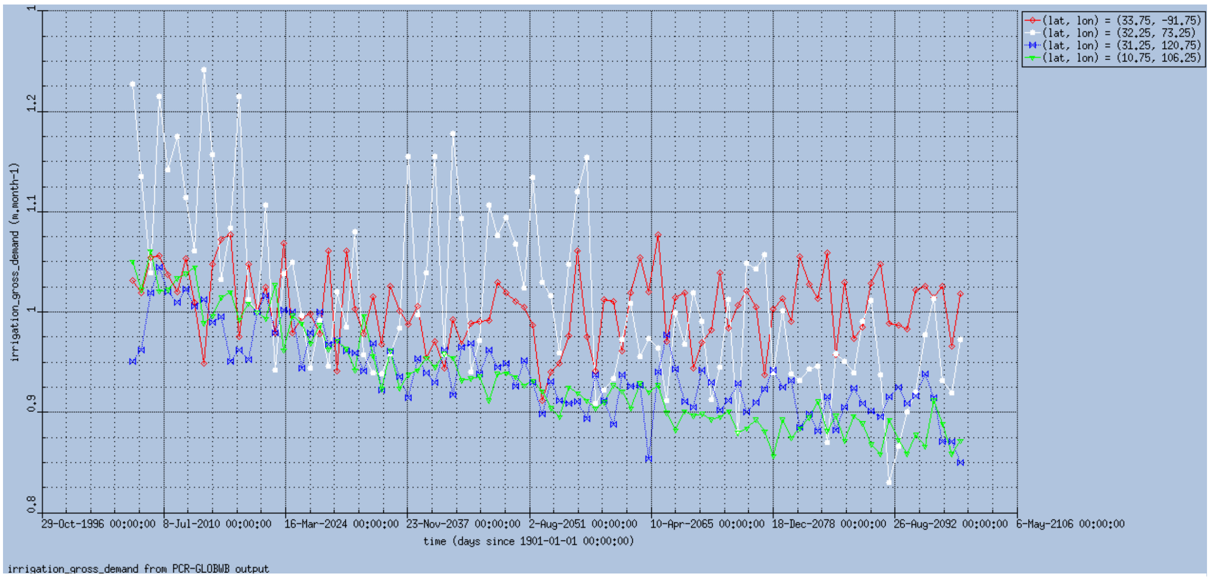

Figure 6-17: Ratios of gross irrigation water requirements in four locations relative to the gross irrigation water requirements in 2000. Gross irrigation water requirements are computed using HadGEM2-ES climate forcing. The four locations correspond to the Mississippi (red), Indus (white), Yellow River (blue), and Mekong river basins (green).

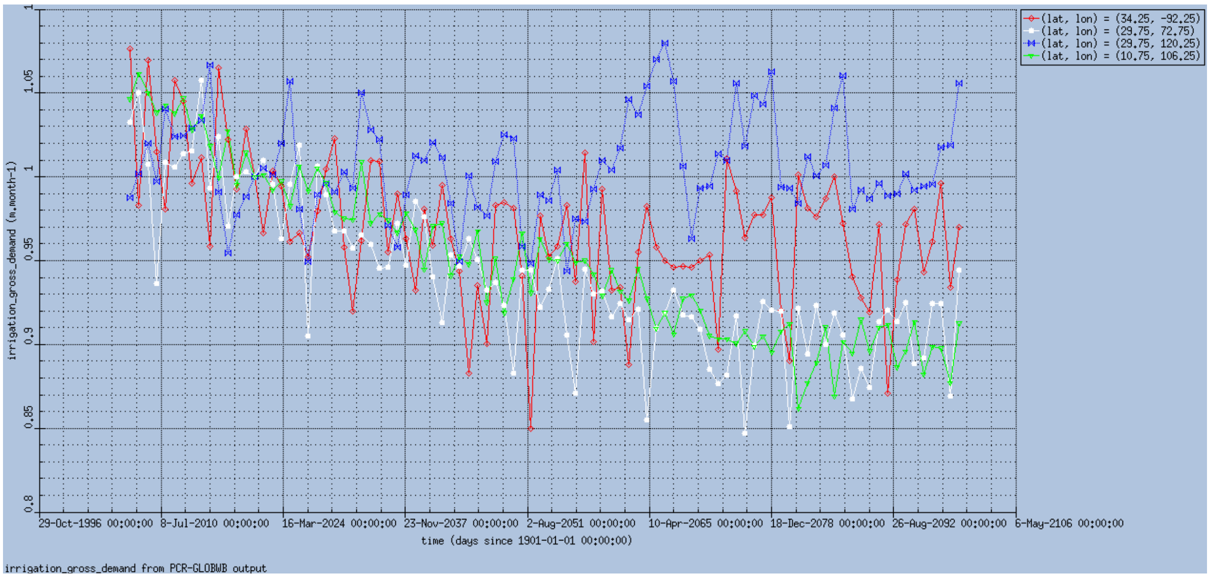

Figure 6-18: Ratios of gross irrigation water requirements in four locations relative to the gross irrigation water requirements in 2000. Gross irrigation water requirements are computed using IPSL-CM5A-LR climate forcing. The four locations correspond to the Mississippi (red), Indus (white), Yellow River (blue), and Mekong river basins (green).

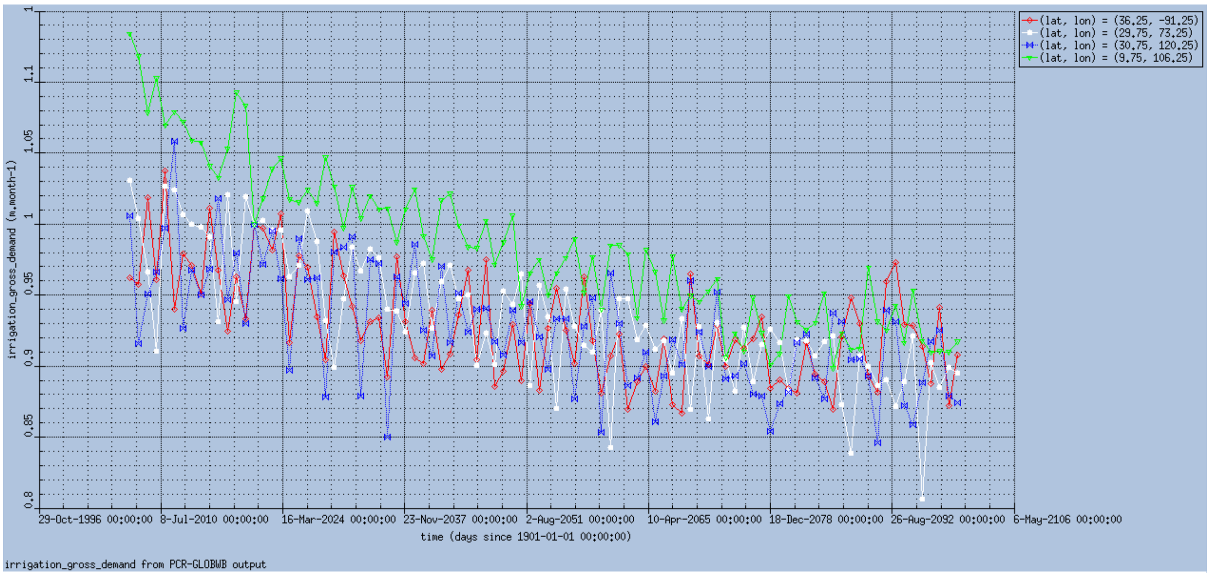

Figure 6-19: Ratios of gross irrigation water requirements in four locations relative to the gross irrigation water requirements in 2000. Gross irrigation water requirements are computed using GFDL-ESM2M climate forcing. The four locations correspond to the Mississippi (red), Indus (white), Yellow River (blue), and Mekong river basins (green).

The ratios presented in the figures 6.17, 6.18, and 6.19 clearly show the impact of climate variability and uncertainty over the signal of irrigation water requirements, with curves of different shapes depending on the GCM projection used, and a moderate (i.e., GFDL-ESM2M) to high variability in the signal (i.e., HadGEM2-ES, IPSL-CM5A-LR). However, all three figures show a slight decrease in future gross irrigation water requirements, of ~ 10 % by the end of the 21st century, with the exception of gross irrigation water requirements in the Mississippi and Indus river basins under climate input from the HadGEM2-ES GCM projection (which remain to ~ 100 % of their levels in 2000, and slowly decrease of ~ 5 % by 2099, respectively), and in the Yellow and Mississippi river basins under climate forcing from the IPSL-CM5A-LR GCM projection (where gross irrigation water requirements remain to ~ 100 % of their levels in 2000, and slowly decrease of ~ 5 % by 2099, respectively). All three results show that, according to the scenarios assumed in this study on irrigation water use efficiency improvement, gross irrigation water requirements can be decreased by 5 to 10 % by the end of the century in heavily irrigated river basins.

7. Discussion

It is important to recall that, in this study, gross irrigation water requirements simulated with the global scale hydrological model PCR-GLOBWB were computed over calendar years, which means that total gross irrigation water requirements may actually be concentrated over shorter periods (i.e., cropping season) and that irrigation water abstractions may be much more important in terms of impact since a large amount of water would be withdrawn over a short period, leaving little time to the environment and the ecosystem to recover.

Our results suggest that gross irrigation water demand is highest over densely populated areas with mainly paddy irrigation. For comparison, the figure 7.1 and 7.2 presented below show irrigated area extent around the year 2010 and the fraction of paddy irrigation per cell, respectively.

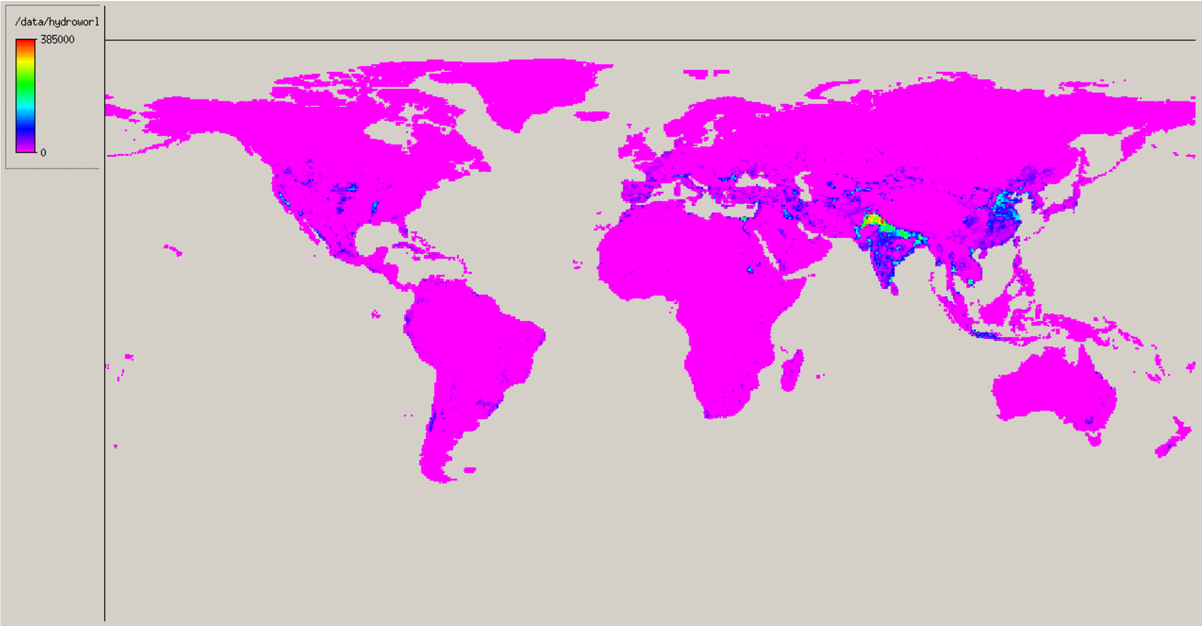

Figure 7-1: Irrigated area per cell in hectares in the year 2000.

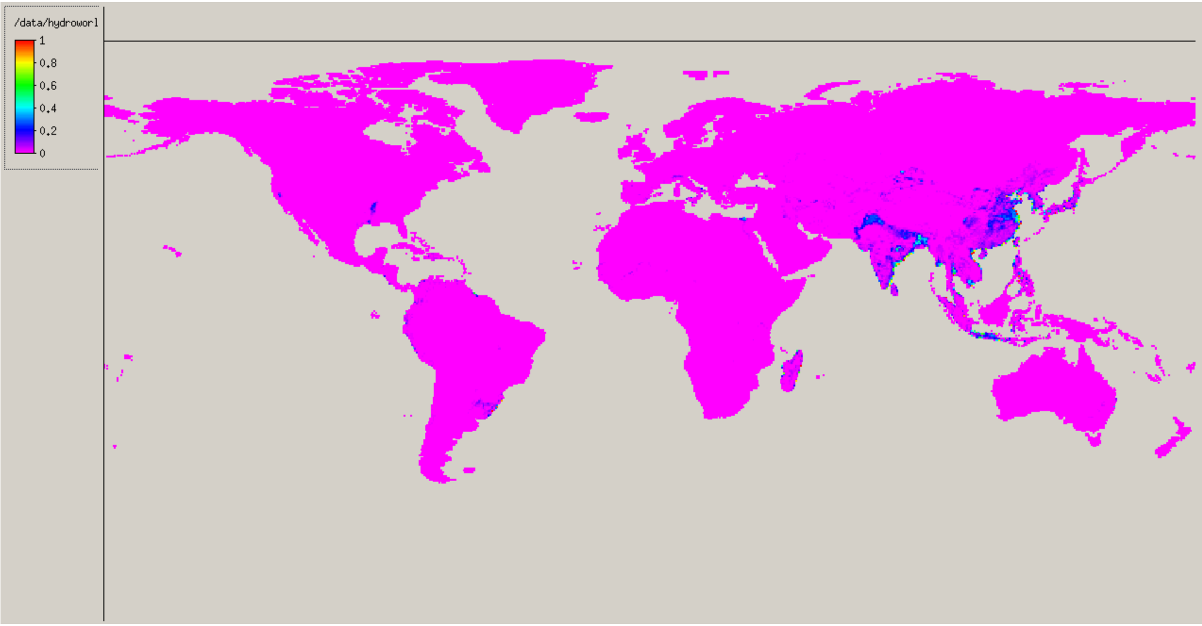

Figure 7-2: Fraction of paddy fields per cell.

Simulated gross irrigation water requirements per basin (i.e., figures 6.12, 6.13, 6.14, and 6.15) and the figures 7.1 and 7.2 show that most impacted basins correspond to heavily irrigated areas, mostly for paddy fields, and that other irrigated regions (i.e., non-paddy irrigated areas) are responsible for low to moderate gross irrigation water demand. This is related to the low efficiency of irrigation over paddy fields, mainly applied via flooding, hence generating high evaporation, direct runoff, and deep percolation water losses.

According to projections from the HadGEM2-ES, IPSL-CM5A-LR, and GFDL-ESM2M GCMs (figure 6.1), annual precipitation rates are expected to increase of roughly 750 km^3 yr^-

^{1}, from ~ 112000 km^3 yr^{-1} in 2020 to ~ 118000 km^3 yr^{-1} by 2100. This will play a major role in reducing irrigation water demand, especially in monsoon-dependent, mainly paddy irrigated areas in Asia. However, this assumption implies an increase in the fraction of accessible blue water, with the construction of new dams and artificial reservoirs in order to increase water supply. The volume of water trapped behind documented dams is estimated between 6000 km^3 and 7000 km^3 [*Shiklomanov and Rodda*, 2003; *Vörösmarty et al*., 2003, 2005], and an estimated 1500 dams are planned or under construction globally, mainly in developing countries [*WRI*, 2004]. Nevertheless, it is not expected that a significantly large number of dams will be constructed over the 21st century, due to increased economics, environmental, and social costs [*Postel et al*., 1996]. The projected increase in precipitation may be beneficial to water supply, especially for irrigation, over river basins equipped with large dams (i.e., over 60 meters high) like for example in the Yangtse river basin in China where 46 large dams are constructed, already in construction, or planned.

Over the historical period 1960-2010, a significant increase in simulated gross irrigation water requirements is observed (figures 6.2 and 6.3): compared to the situation in 1960, ~ 3810 more cubic kilometres of water were required for irrigation purposes in 2000. The magnitude of this increase (i.e., more than doubling) corresponds to previous assessments of irrigation water requirements (e.g., *Döll and Siebert*, 2002; *Hanasaki et al.*, 2006; *Siebert and Döll*, 2007; *Hanasaki et al*., 2008a,b; *Rost et al.*, 2008; *Wisser et al*., 2010; *Wada et al*., 2011b) and to the increase in irrigated area that occurred over the 20th century [*Freydank and Siebert*, 2008; *Portmann et al.*, 2008, 2010; *Wisser et al*., 2010; *Wada et al*., 2011b].

When climate projections are used in the model (figures 6.2 to 6.9), a small decrease in annual gross irrigation water demand, comprised between ~ 175 km^3 yr^{-1} and ~ 560 km^3 yr^{-1}, is observed over the future period 2006-2099. When climate conditions from the CRU TS 3.21 dataset are repeated over the 21st century, hence avoiding climate uncertainty and variability signals in the results, the decrease in annual gross irrigation water requirements is in the same order of magnitude of the highest value observed when using GCMs climate input, that is, ~ 560 km^3 yr^{-1}. This highlights the importance of our irrigation water use efficiencies scenarios, as over the future period, only irrigation project efficiency is not kept at contemporary levels. All other non-meteorological variables are kept constant at their 2010 value, with the most important being irrigated areas and surface water bodies extent in 2010 (see table 5.2). In our modeling configuration, a uniform irrigation efficiency improvement of roughly 20 % by 2080 based on irrigation efficiency per country in 2000 can save a maximum of about half a thousand cubic kilometres of water per year. When climate variability and uncertainties are included, this drops to a lower average value of ~ 350 km^3 yr^{-1}. The ratios of gross irrigation water requirements presented in the figures 6.17, 6.18, and 6.19 show that irrigation water use efficiencies improvement, as implemented in our model, can help reducing gross irrigation water requirements by a maximum of 10 % by the end of the 21st century compared to contemporary levels.

Unsurprisingly, river basins that are subjected to the most important irrigation water demand correspond to heavily irrigated areas (i.e., North eastern China, India, Japan, Indonesia, South central Asia, South central America, the Nile and Mississippi river basins, and around the Mediterranean basin). The improvement of irrigation water use efficiencies will lead to the most important decrease in gross irrigation water requirements over these areas. In addition, the calculation of gross irrigation water demand at the basin scale (figures 6.12 to 6.14) highlights the dramatic impact irrigation water requirements may have on a single river basin, with for example nearly 3 m month^{-1} of irrigation water required in North eastern China or in Indonesia Java Island .Inversely, it was observed that irrigation water use efficiencies improvement can lead to the disappearance of irrigation effects over slightly irrigated basins (e.g., in the Central USA, and in the South western Russia).

The decrease in gross irrigation water requirements observed in this study after implementing irrigation water use efficiencies improvement should be evaluated with precaution, since a large fraction of abstracted irrigation water is subsequently consumed by the crops and not returned to the environment. This means that, although irrigation activities play a significant role on return flows and in the indirect supply of water to the environment, the magnitude of irrigation impact on the alleviation of non-renewable groundwater abstraction and on irrigation-dependent ecosystems may decrease with the improvement of irrigation water use efficiencies [*Perry*, 2007, 2009].

The figure 7.3 presented below shows mean annual water scarcity index, based on annual water availability and demand simulated with the global hydrological model PCR-GLOBWB, computed by *Wada et al*. [2011b].

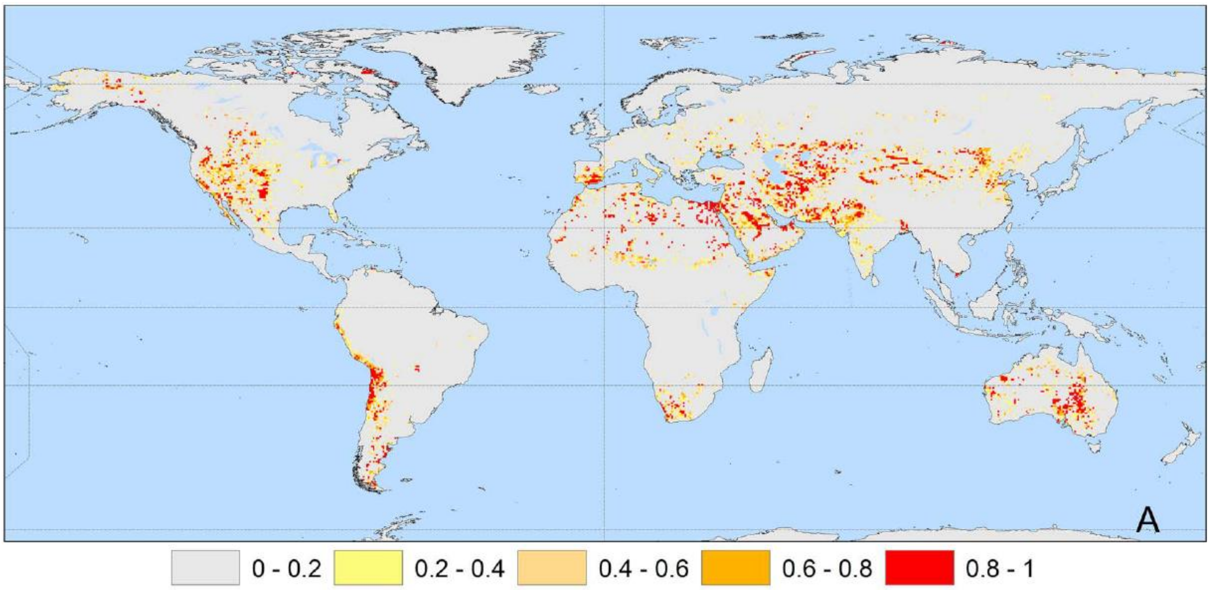

Figure 7-3: Mean annual water scarcity index based on annual water availability and demand. From *Wada et al*. [2011b].

From the comparison of this document and our study results, it appears that difficulties in irrigation water supply will emerge in numerous locations over the future if no improvements in irrigation water use efficiencies and in the sustainability of water resources exploitation are carried out, for example in Southern Spain, North eastern China, in the Indus river basin, and over the Nile Delta. The alleviation of gross irrigation water requirements by irrigation efficiency improvement will help satisfying more crop water requirements in these areas, which means that, ultimately, less water would be abstracted from the source to satisfy the same amount of irrigation water demand. This, in turn, can significantly reduce non-renewable abstractions, hence groundwater depletion, and increase water availability in order to subsequently satisfy more crop requirements in case irrigated area is increased over the future. In addition, the improvement of irrigation efficiency can also help support more ecosystem water requirements, thus avoiding degradation of natural processes.

As mentioned, irrigated area and population were kept at 2010 levels. It is however unlikely that irrigated area will remain the same over the 21st century, even more concerning the global population. Few studies have provided information on the future extent of irrigated areas. However, no significant increase in irrigated area is expected over the next few decades [*Bruinsma*, 2003; *FAO*, 2006a; *Alexandratos and Bruinsma*, 2012]. In addition, little information is currently available on crop varieties and cropping intensities over the 21st century. These two factors may have a significant impact on future irrigation water requirements, in particular in the context of increasing CO_2 concentrations. Increased CO_2 concentrations have proved to cause a decrease in crop water requirements of ~ 10 % [*Taub*, 2010], which in turn means that higher levels of soil moisture and runoff would subsequently be available for later use [*Leakey et al.*, 2009]. Further investigation into the impact of these factors on water use and availability is required, along with rigorous monitoring of irrigation water abstractions and impact on water resources.

8. Conclusion

From our study, it can be concluded that the improvement of irrigation water use efficiencies will play a significant role in irrigation water abstractions over the 21st century. Improving irrigation efficiency will be beneficial in all basins, at all locations. Irrigation is and will most likely remain the most important water demand and water consumption sector, yet will require higher volumes of water over the future due to growing human population and increased living standards of population in developing and under developed countries. However, it is not expected that a significant increase in accessible water will occur, and water scarcity will remain an issue in numerous areas worldwide. Consequently, it is crucial that the efficiency of irrigation systems is increased over the future, especially conveyance and application efficiencies, in order to make more water available for further use, waste less water, alleviate the impact of irrigation on water resources, and lead to increased crop yields and better food supply to the population.

Therefore, a next step in the assessment of irrigation water use on water resources would be to study the magnitude of efficiency improvements per country in relation to the economic and technological degree of development, how future irrigated area will develop, which crops will be cultivated there, and how much of the future global population irrigated crops will be able to support.

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