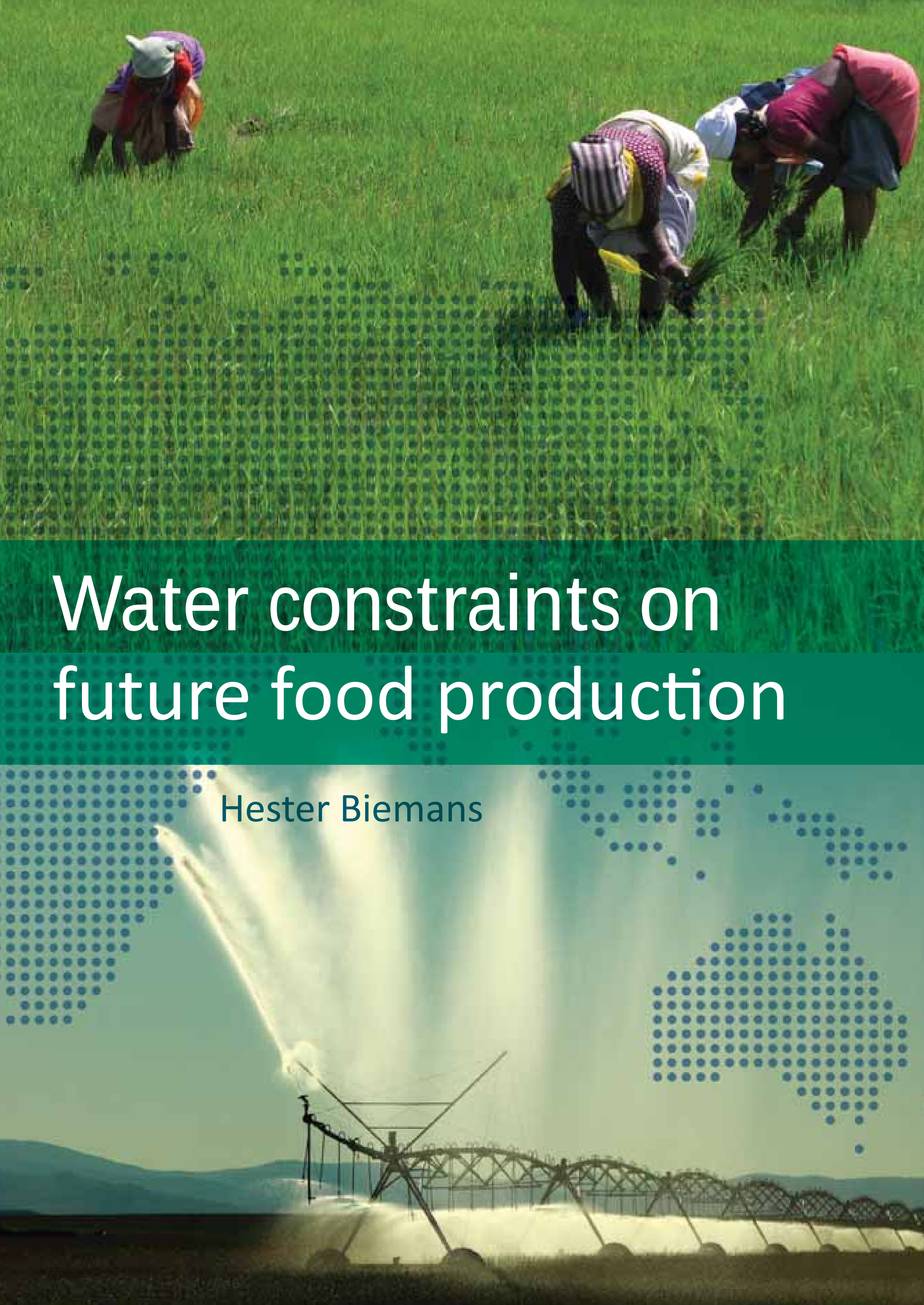


Water constraints on future food production

Hester Biemans

Water constraints on future food production

Hester Biemans

Thesis committee

Promotor

Prof. dr. P. Kabat

Director/CEO at the International Institute for Applied Systems Analysis, Laxenburg, Austria

Professor of Earth System Science, Wageningen University

Co-promotors

Dr. R.W.A. Hutjes

Senior scientist, Earth System Science and Climate Change Group, Alterra, Wageningen UR

Dr. F. Ludwig

Senior scientist, Earth System Science and Climate Change Group, Wageningen University

Other members

Prof. dr. C.J. Vörösmarty, City University of New York, USA

Prof. dr. A.Y. Hoekstra, University of Twente, the Netherlands

Prof. dr. R. Uijlenhoet, Wageningen University, the Netherlands

Dr. E. Stehfest, Netherlands Environmental Assessment Agency (PBL), the Netherlands

This research was conducted under the auspices of the SENSE research school.

Water constraints on future food production

Hester Biemans

Thesis

submitted in fulfillment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Friday 5 October 2012
at 1.30 p.m. in the Aula.

Hester Biemans
Water constraints on future food production
168 pages

Thesis, Wageningen University, The Netherlands (2012)
With references, with summaries in English and Dutch

ISBN 978-94-6173-357-3

Table of contents

1

General Introduction

1.1 Background

Water plays a central role in many natural and human processes. Its availability is essential for natural vegetation and agricultural production, for human settlements and industry. The total volume of water on Earth is about 1400 million km^3, but only 2,5%, or around 35 million km^3, is fresh water. Most of this freshwater is "locked up" in the form of permanent ice or snow, or in deep groundwater aquifers, which makes the fraction usable for human use less than 1% of all freshwater (WWAP, 2006). Although this amount is still more than enough to fulfil all human needs, it is the uneven distribution in time and place that can make water a scarce resource in some regions.

Water from rivers, lakes, human build reservoirs and groundwater is extracted to supply water to irrigated agriculture, households and industry. This water is referred to as 'blue water' (as opposed to precipitation, which is called 'green water'). Estimates of current global blue water extractions are around 4000 km^3 yr^{-1}. Irrigated agriculture is by far the largest user of blue water and is responsible for about 70% of global water withdrawals (Oki and Kanae, 2006).

Although irrigation has always played a role in global crop production, it has especially increased during the second part of the 20th century. Driven by increases in food demand due to population and economic growth, people have tried to increase the level of control over the hydrological cycle, in order to make more water available at the time and place needed. Irrigation water is supplied to crops when precipitation is insufficient, and also allows for agriculture where it would otherwise be impossible due to low rainfall. Yields from irrigated agriculture are generally higher than from rainfed agriculture.

During the last 50 years, the global irrigated area roughly doubled (Foley et al., 2011) towards 276 Mha around the year 2000 (Siebert et al., 2005). By transporting water from rivers, lakes, reservoirs or groundwater to supply irrigated fields, the water use in agriculture significantly increased. Consequently, the fraction of the global food production depending on irrigation grew. Currently 33% of the total global crop production is harvested from irrigated lands, which occupy only 17% of the total agricultural area (Portmann et al., 2010).

The construction of large dams has further increased human control over the hydrological cycle, and the volume of water that is accessible to exploit. Artificial reservoirs can store water during wet periods to be available in dry periods. Not only do reservoirs increase the average residence time of water in rivers, they also increase the total water storage in a river system (Vörösmarty et al., 2003; Vörösmarty et al., 1997). The International Committee on Large Dams (ICOLD, 2007) registered 30.000 artificial reservoirs worldwide, with an estimated cumulative capacity of 8000 km^3, which is 20% of the mean annual global runoff. More than one third of those reservoirs are built for irrigation purposes (Haddeland et al., 2006b). The World

Commission on Dams estimated that 30-40% of the irrigated areas worldwide rely on dams and that those dams contribute to 12-16% of the world food production (WCD, 2000).
Both expansion of irrigation and construction of reservoirs have been of major importance for the increase in the world food production. But there is reason for concern. There is a limit to the amount of freshwater that can be used sustainably (Rockstrom et al., 2009). About one third of the world's population is already living in countries suffering from 'medium' (where annual water withdrawal is more than 20 % of renewable freshwater resources) to 'high' water stress (withdrawal >40%) (Vörösmarty et al., 2000c), and it is questionable if sufficient water resources will be available to sustain a further growing future food production (Godfray et al., 2010).
The population is likely to increase to 9 to 12 billion in the coming century (Grubler et al., 2007; Nakicenovic and Swart, 2000). This is will be accompanied with strong economic growth in some parts of the world, leading to a further increase in water demands.
On top of that, there is climate change, which will affect both water availability and demand. Higher greenhouse gas concentrations in the atmosphere result in an increase in the available energy on the surface of the Earth, leading to a higher temperature and an 'intensification' of the hydrological cycle at global scale (Kabat et al., 2004). The effect of this intensification is still uncertain. Global Climate Models (GCMs) show consistent projections of changes in precipitation for several regions: drying trends in the Mediterranean, southern Africa, the Middle East and South East Australia and more precipitation at high latitudes: Canada and Russia. However, there is more uncertainty about the future precipitation in India, China, West Africa and almost the whole of south America (IPCC, 2007). GCM results further suggest that climate change will result in a higher variability in rainfall, both intra-annual as inter-annual, which might lead to more severe water stress in single years.
Several studies already showed projections of increasing water stress in the future, due to the combined effect of socio economic changes leading to higher water demand, and climate change leading to changes in water availability (e.g. Alcamo et al., 2003b; Arnell, 2004). However, water scarcity might even become more severe than suggested in these studies, because their indicators mask potential temporal (intra- and inter-annual) and spatial (within a basin) variations in water stress (Vörösmarty et al., 2000c). Further, besides showing that there is and will be a mismatch between water demand and supply, they do not quantify what is the impact of this water stress on different sectors, e.g. agriculture, electricity production or households.
The central question of this thesis is whether there will be enough water to sustain global food production towards the end of the 21^{st} century. As both climate change and food security are issues of global scale, in which regions are connected by physical or economic relations and dependencies, this question needs a global analysis. Answering this question requires first a

quantification of current and future water availability for agriculture. Next, estimates of where and by how much water demand is going to change are needed, followed by an assessment of the impacts of water scarcity on food production. Finally, potential solutions to increase the food security related to water scarcity should be investigated.

1.2 Model approach for agricultural and water resources assessments

Understanding the processes influencing current and future water availability, irrigation water demand and crop production requires an extensive understanding of the global hydrological cycle and its interactions with vegetation, climate and humans. Integrated earth system models can help in understanding this interlinked system, provided that important processes and feedbacks are included at sufficient spatial and temporal resolution.

1.2.1 IMAGE

The Integrated Model to Assess the Global Environment (IMAGE) is an integrated assessment model that is used for the development and analysis of scenarios of global environmental change (figure 1.1). It simulates (amongst others) future changes in land use and agricultural production. Land use change calculations start from scenarios for agricultural demand, trade and crop production in 24 world regions. Those scenarios are developed using an agricultural economy model, based on a set of assumptions on socio-economic developments (Eickhout et al., 2006). Subsequently, the projected regional production is allocated to 0.5 degree grids, on existing and new agricultural areas, by accounting for the effect of climate change as well as management on crop yields (MNP, 2006).

IMAGE is a suitable tool to study the future agricultural system as it combines the effects of climate change and socio economic changes on land use and food production. However, there is no representation of water resources availability and therefore IMAGE is not yet suitable to address (blue) water limitations on future food production. Irrigated yields are computed irrespective of water limitations, and therefore constraints imposed by water stress are not taken into account. Moreover, the current version of IMAGE does not simulate a change of irrigated area into the future, although the Food and Agriculture Organisation (FAO) and others expect that a further expansion of irrigated areas will be necessary to meet future production needs (FAO, 2006) (e.g. Molden, 2007; Rosegrant et al., 2002) .

In order to incorporate water availability in the calculation of current and future irrigated production, IMAGE needs to be extended with a global hydrological model that is able to

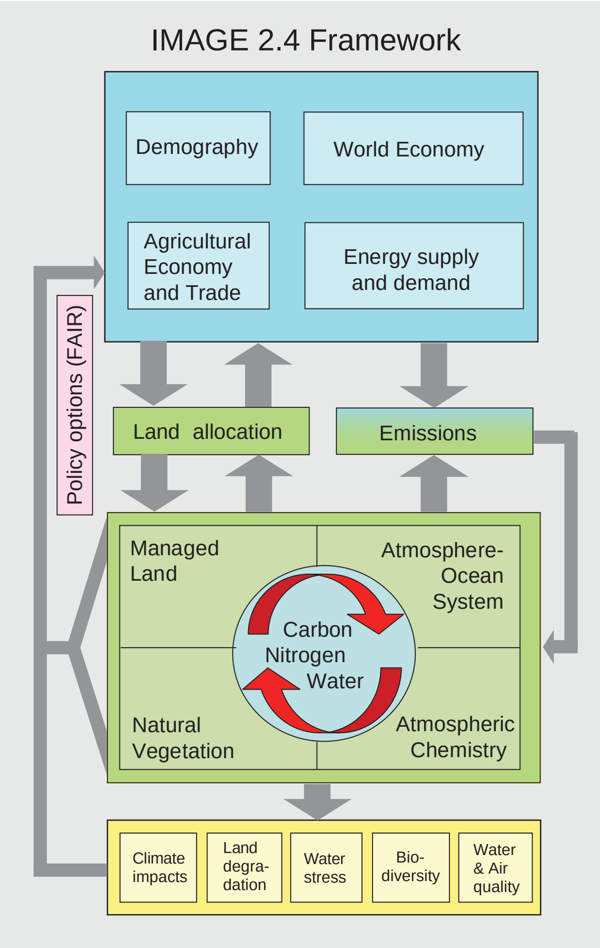


Figure 1.1 Schematic overview of IMAGE 2.4 (MNP, 2006)

simulate water availability and demand at 0.5 degree grids under different land use and climate change scenarios. Furthermore the model should be able to represent irrigation and reservoir operations. In order to calculate effects of water shortage on crop production, and to keep fluxes consistent between submodels, it needs to be integrated with the crop module of IMAGE. From a technical perspective, the hydrological model should have a complexity and runtime that is in balance with other modules.

1.2.2 Global Hydrological Models and LPJmL

Global hydrological models are developed to estimate fluxes of the world hydrological cycle driven by climate input and soil and vegetation characteristics, e.g. VIC (Nijssen et al., 2001), TRIP (Oki et al., 2003), WBM (Vörösmarty et al., 1998), MacPDM (Arnell, 1999b), WaterGAP (Alcamo et al., 2003a; Döll et al., 2003) and LPJmL (Gerten et al., 2004; Rost et al., 2008). Those models typically simulate evaporation, runoff and riverflow on 0.5 to 1 degree gridcells at daily time steps, but have different levels of complexity (Haddeland et al., 2011). Most of those models have been applied to simulate the 'naturalized' hydrological cycle (as if there were no irrigation extractions and reservoir operations), both for the 20th century as under climate change (IPCC, 2007).

In recent years, some of the global hydrological models have been improved to include, to a certain extent, a representation of human alterations to the hydrological cycle. They now include calculations of irrigation water requirements and withdrawals (Döll and Siebert, 2002; Haddeland et al., 2006a; Rost et al., 2008; Wisser et al., 2008). Plant irrigation requirements are calculated based on soil moisture, soil type, crop type and climate. The irrigation withdrawals than depend on the extent of irrigated area (Siebert et al., 2005), regional irrigation efficiency and the amount of water available.

To improve the simulation of temporal variability in streamflow, globally applicable algorithms for the operation of large reservoirs have been developed in two large scale hydrological models (Haddeland et al., 2006b; Hanasaki et al., 2006). Those reservoir operation schemes provide general water release algorithms based on the operational purpose of the dam.

Global hydrological models are getting more complex. The including of more relevant processes as described above leads to better estimates of water availability and demand. Still, the assessment of impacts of water shortage is often relatively simple. Water stress is usually calculated by a mean annual withdrawal-to-availability ratio at basin scale (Alcamo et al., 2003b) or a per capita water availability based on annual runoff (Arnell, 2004). However, both water availability and demand are variable in time and space and should therefore be confronted at higher spatial and temporal resolutions. To address the impact on water shortage on food production, sector specific water stress indicators for the agricultural sector have to be developed, incorporating a quantification of the effect of water shortages on production.

The global vegetation and hydrological model LPJmL was chosen for all analyses in this thesis. This model contains a relatively simple representation of the hydrological cycle compared to some other models, but its runtime allows for implementation in IMAGE. Gerten et al. (2004) showed that the model was capable of simulating monthly hydrological fluxes comparable to other global hydrological models and Rost et al. (2008) implemented a routing algorithm to account for lateral flows and irrigation withdrawals (figure 1.2).

LPJmL was originally developed and tested as dynamic global vegetation model (DGVM), simulating the establishment, development and mortality of natural vegetation (Sitch et al., 2003). The model was extended with a crop model with representations for both rainfed and irrigated crops (Bondeau et al., 2007). Especially this feature of LPJmL, being a combination of a crop production model with a hydrological model, makes the model a very suitable tool to study the impacts of water shortage on crop production in a quantitative way. However, the

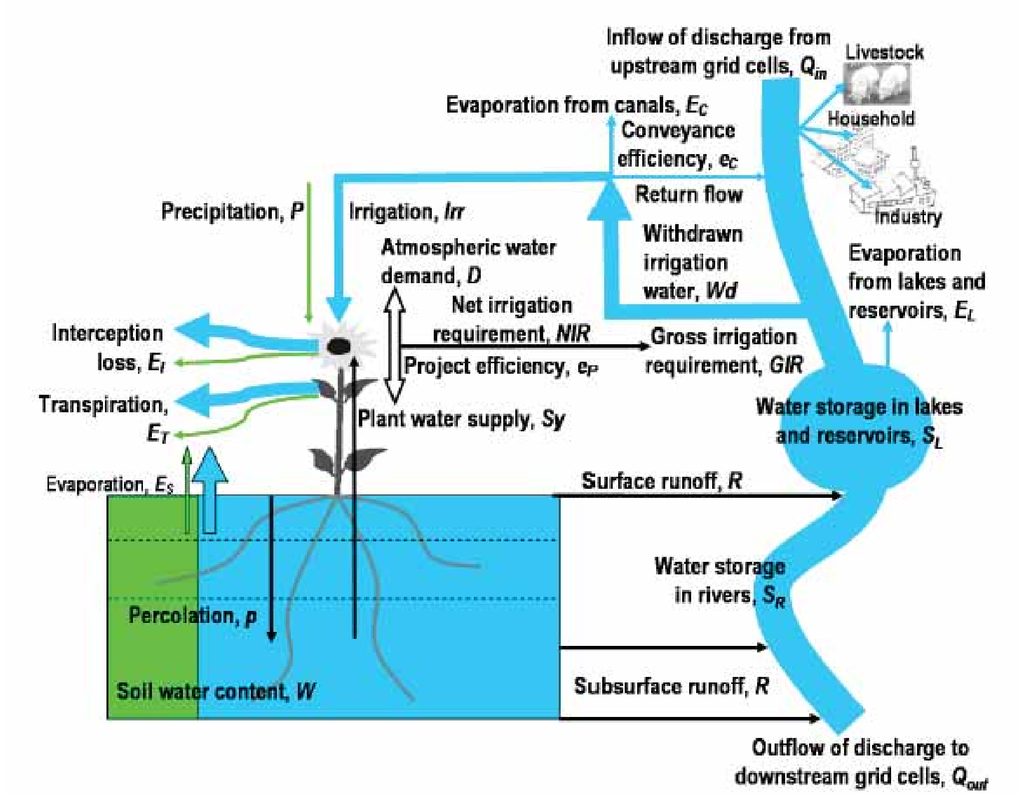


Figure 1.2 Schematic diagram of the hydrological components in LPJmL (Rost et al., 2008)

hydrological components of LPJmL needed more validation and improvements, which are described in this thesis.

1.3 Objectives

The research objective in this thesis is to assess the combined effect of future socio economic and climate changes on water supply and demand, and the associated impact on agricultural production towards 2100.

In order to reach this objective, five research steps and corresponding questions were formulated:

- How much water is currently available in global river systems? (ch 2)
- How did the construction of large reservoirs during the 20th century contribute to water availability for agriculture? (ch 3)
- How will agricultural water demand and water availability change as a result of socio economic and climate change? (ch 4)

- How will future food production be affected if there is an irrigation water shortage? (ch 4)
- What is the potential effect of adaptation measures aiming at reducing water related crop production losses? (ch 5)

1.4 Outline of the thesis

This thesis comprises 6 chapters, including the introduction. Each of the subsequent chapters addresses at least one of the research questions and builds upon results and conclusions of the previous chapter.

Chapter 2 describes an evaluation of the hydrology of LPJmL. The simulation of discharge for a large set of 300 rivers is validated. Those rivers are situated in different continents, different climatic zones and have different levels of human interactions. The validation accounts for the uncertainty in precipitation input data and explores to what extent this effects the uncertainty in simulated discharge, and hence the validation process.

In Chapter 3 LPJmL is further developed towards a water resources model. Here, the model is extended with a module to simulate the operation of large human build reservoirs. This module simulates both the outflow regimes of large reservoirs to rivers, as well as the distribution of water to irrigated areas. The extended model is validated and used to estimate the contribution of large reservoirs to irrigation water supply during the 20th century.

Chapters 2 and 3 focus on an improved understanding of the availability and use of water resources in the 20th century, as well as validation and testing of the model. Chapter 4 and 5 apply the model to explore the water resources in relation to food production towards 2100.

In chapter 4 the water requirements for future food production are estimated, by accounting for the effect of climate change and land use change, following two contrasting SRES scenarios. Subsequently regions where future food demand may not be met due to water shortage are identified.

Chapter 5 focusses on river basins on the Indian subcontinent. In chapter 4 this region is identified as being at risk of not achieving the required food production. It is a rapidly changing region where both climate change and socio-economic changes are expected to have a large impact on available water resources and food security. A spatially explicit quantitative analysis of water availability for food production is made in the absence or presence of two different adaptation options: an overall improvement of the irrigation efficiency, and an increase of the storage capacity of existing large reservoirs.

Finally chapter 6 presents a compilation of the main findings of the thesis, it discusses uncertainties and limitation of the chosen approach. Further, it presents an outlook to a new research agenda for global hydrological and agricultural assessments, and concludes with the main messages drawn from this work.

2

Effects of precipitation uncertainty on discharge calculations for main river basins

This study quantifies the uncertainty in discharge calculations caused by uncertainty in precipitation input for 294 river basins worldwide. Seven global gridded precipitation datasets are compared at river basin scale in terms of mean annual and seasonal precipitation. The representation of seasonality is similar in all datasets, but the uncertainty in mean annual precipitation is large, especially in mountainous, arctic and small basins. The average precipitation uncertainty in a basin is 30%, but there are strong differences between the basins.
The effect of this precipitation uncertainty on mean annual and seasonal discharge was assessed using the uncalibrated dynamic global vegetation and hydrology model LPJmL, yielding even larger uncertainties in discharge (average 90%). For 95 basins (out of 213 basins for which measurements were available) calibration of model parameters is problematic, because the observed discharge falls within the uncertainty of the simulated discharge. A method is presented to account for precipitation uncertainty in discharge simulations.
Supplementary to this paper an online-database is released. It contains extensive analyses of 7 precipitation datasets, calculated discharge accounting for the precipitation uncertainty and comparisons with station observations for all 294 basins (www.climatexchange.nl/projects/JHM).

Based on:

Biemans, H., R.W.A. Hutjes, P. Kabat, B.J. Strengers, D. Gerten and S. Rost (2009). Effects of precipitation uncertainty on discharge calculations for main river basins. Journal of Hydrometeorology. Volume 10, 1011-1025

2.1 Introduction

There is a growing concern about increasing water scarcity in many regions of the world, as climate change on the one hand, and increasing human water use on the other, can put increasing pressure on the world's water resources (CSD, 1997; Kundzewicz et al., 2007; World Water Council, 2000).

Understanding the processes leading to (repetitive) droughts and floods requires an extensive understanding of the global hydrological cycle and its interactions with vegetation, climate and humans (Kabat et al., 2004). Not only should average annual water availability be quantified with certainty, but also the spatial and temporal distribution of water availability. There are several studies that calculate soil moisture, runoff and its accumulation in discharge based on climate input, soil and vegetation characteristics using global scale hydrological models (e.g. Alcamo et al., 2003b; Arnell, 1999b; Gerten et al., 2004; Nijssen et al., 2001; Oki et al., 2001; Vörösmarty et al., 1998). Most of these models have been used to simulate current discharge patterns, but a number of global assessments on the influence of climate change on future water resources exist (e.g. Alcamo et al., 2007; Arnell, 1999a; Arnell, 2003; Barnett et al., 2005; Bergstrom et al., 2001; Milly et al., 2005; Vörösmarty et al., 2000c).

For a reliable quantitative assessment of future water resources, it is important to first gain trust in the simulation of current water availability. This can be done by validating the global model to observed discharges, for which data are available globally (GRDC, 2007). Discharge is the integrator of the water balance over large areas and can be regarded as the water availability in different sectors.

Few global hydrological models have been validated and calibrated to discharge observations in order to reduce the bias between observations and simulations. This was done by adjusting the models' parameters (Nijssen et al., 2001), or by applying a simple correction parameter (Döll et al., 2003). However, the bias between observations and simulations cannot always be attributed to the models designs. If, for example, the precipitation input data in a particular basin is too low, it is logical that the simulated streamflow becomes too low, even though the parameterization of the runoff generation process may be physically correct. Tuning the model to observed discharge can thus result in a compensation of the underestimated or overestimated precipitation leading to an unrealistic partitioning of precipitation between runoff and other water balance terms. Therefore, the uncertainty in model simulations arising from different factors should be taken into account before calibrating the models' parameters. Wind induced undercatch of solid precipitation (Adam and Lettenmaier, 2003) and underestimation of precipitation in topographically complex regions (Adam et al., 2006) are well known sources of errors in precipitation products derived from rain gauge measurements. Tian et al. (2007) compared water balance calculations with undercatch-corrected and uncorrected precipitation data and demonstrated that using bias corrected precipitation resulted in an increase in computed streamflow of 5-25% in Northern latitudes.

The question which precipitation dataset is the most accurate for forcing of hydrological models is posed in several studies, but has not yet been answered with consensus. Berezovskaya et al. (2004) showed inconsistencies between runoff data and three precipitation datasets for three large Siberian rivers. Their analysis suggests a poor quality of either the runoff or precipitation datasets or both. Pavelsky and Smith (2006) used discharge observations of 198 Arctic rivers to assess the quality of four global precipitation sets and concluded that observational datasets cover the trends significantly better than two reanalysis products. At global scale however, Voisin et al. (2008) evaluated a reanalysis precipitation product more suitable than a satellite derived precipitation dataset for use in a hydrological model, mainly because of the high temporal resolution of the reanalysis product.

Fekete et al. (2004) demonstrated the impact of uncertainties in precipitation input on runoff estimates at a grid scale by forcing a global water balance model with six different global precipitation datasets. This analysis showed that the uncertainty in precipitation translates to at least the same and typically much greater uncertainty in runoff in relative terms. Although the sources of the differences between the datasets were not identified, Fekete et al.'s (2004) study demonstrated the importance of taking a close look at the climate input data that is used to force the hydrological model. However, they did not compare the datasets on a basin scale, which is the common scale for water resources assessments.

The problem of uncertainties in input data for global hydrological models and the resulting over- or underestimations of streamflow in several basins has been identified in several papers (e.g. Döll et al., 2003; Gerten et al., 2004; Nijssen et al., 2001), but its individual contribution to overall uncertainty has to our knowledge not yet been quantified at global scale. Although there are possible uncertainties in all input datasets (e.g. soil, land use, temperature), in this paper we will focus on the impact of uncertainty in precipitation data, which we expect to be the largest source of uncertainty from input data.

For water resources assessments, the intra-annual dynamics of discharge are important, because both water demand and supply vary over the year. Therefore, the impact of uncertainty should also be investigated on a seasonal time scale.

The objective of this paper is to quantify the global distribution of the uncertainty in annual as well as seasonal estimates of precipitation on a basin scale and the resulting uncertainty in discharge estimates as computed by the LPJmL model (Bondeau et al., 2007; Rost et al., 2008). Based on the results, consequences of this uncertainty for validation and calibration of global hydrological models are discussed. Specifically, we compare the variations between seven global gridded precipitation datasets at a basin scale, analyze the simulated variations in discharge on a mean annual as well as a mean seasonal time scale, and compare the outcomes with observations for 294 basins around the world. More detailed analyses are presented for a selection of 16 basins located in different climate zones and with different hydrological properties. The analysis for all 294 basins can be consulted in an online database.

Section 2 gives an overview of the method: the seven global precipitation datasets used, other input data for the LPJmL model, a brief model description and the data used for validation. In section 3 the results of the analysis are presented in three parts: (1) the precipitation uncertainty, (2) the impacts of this uncertainty on discharge simulations and the (3) comparison with observed discharge. Section 4 discusses the implications of these results for validating, developing and calibrating global hydrological models and concludes on the representation of uncertainty in modeling results.

2.2 Methods and Data

2.2.1 Precipitation input

In this study we use seven global gridded precipitation sets (Table 2.1) and compare them at basin scale. These datasets differ with respect to the original data sources that are used, the interpolation method and the eventual correction factors applied. The datasets are selected based on their spatial coverage (global) and their temporal coverage (at least 20 year time series).

The *CRU* dataset has been developed by the Climate Research Unit of the University of East Anglia. It consists of a climatology (New et al., 1999) and monthly anomalies to this climatology (New et al., 2000) at a global 0.5° resolution, of which monthly values for precipitation, temperature, cloud cover and number of wet days per month are used for the present study.

Table 2.1. Main characteristics of the 7 global gridded precipitation sets used in this study.

Dataset	Res	Period	Source	Description
CRU	0.5	1901-2002	http://www.cru.uea.ac.uk/cru/data/hrg.htm	New et al., 1999, 2000
CRU-PIK	0.5	1901-2003	Potsdam Institute for Climate Impact Research	Österle et al., 2003
MW	0.5	1900-2006	http://climate.geog.udel.edu/~climate/	Matsuura and Wilmott, 2007
GPCC	0.5	1951-2000	http://www.dwd.de	Beck et al., 2005
GPCP	2.5	1979-2007	http://cics.umd.edu/~yin/GPCP/main.html	Adler et al., 2003
CMAP	2.5	1979-2007	http://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.cmap.html	CPC, 2007
ADAM	0.5	1979-1999	http://www.ce.washington.edu/~jenny/global_sim.html	Adam et al., 2006

The dataset has recently been updated (CRU TS 2.1, (Mitchell and Jones, 2005)) for the years 1901-2002. *CRU* is chosen as our reference dataset, because it provides a full forcing dataset to run the model (precipitation, temperature, number of wet days and cloud cover).

Österle et al. (2003) showed that the time series of temperature and precipitation in the first *CRU* database that covers the period 1901-1998 (New et al., 2000) were inflicted with inhomogeneities. These inhomogeneities were adapted for each gridcell by a correction procedure (Österle et al., 2003). In order to extend the data to 1999-2003 an earlier version of the GPCC data (described below) for each 1°x1° grid cell was used and interpolated onto a 0.5° grid based on the correlations between the grid cells derived from the original *CRU* precipitation data between 1986-1998. The precipitation dataset that has been developed by Österle et al. (2003) is referred to herein as *CRU-PIK*.

The global precipitation dataset *MW* has been developed by Matsuura and Willmott (2007). It covers the period 1900-2006 and comprises monthly time series at 0.5º resolution. This precipitation dataset is based only on station data from several sources. Station climatology from the Legates and Willmott (1990) unadjusted (for rain gauge undercatch) archive were used as a part of the background climatology. Station precipitation values were not adjusted to reduce rain gauge undercatch bias. The stations were not checked for temporal heterogeneities, because the main goal of this dataset was to represent spatial patterns of rainfall rather than homogenous time series.

The most recent version of the *GPCC* global precipitation dataset (Beck et al., 2005) consists of monthly precipitation fields on a 0.5º grid for the period 1951-2000. The dataset is based only on station observations, which have met high demands concerning the quality and temporal coverage. Therefore this dataset is mainly suitable to study temporal variability. Interpolation has been done using ordinary kriging.

The Global Precipitation Climatology Project (*GPCP*), which is a part of the Global Energy and Water Cycle Experiment (GEWEX), developed a monthly precipitation dataset for 1979 to 2003 (Adler et al., 2003). The resolution of this dataset is 2.5°. It is based on a previous version described by Huffman et al. (1997) and was derived by merging satellite and surface rain gauge data. The gauge data have been corrected for systematic errors using a monthly correction factor as derived by Legates (1987).

The Climate Prediction Center Merged Analysis of Precipitation (*CMAP*) is a dataset which comprises both pentad and monthly analyses of global precipitation (CPC, 2008; Xie and Arkin, 1997). Observations from rain gauges were merged with precipitation estimates from several satellite-based algorithms (infrared and microwave). The analyses were performed on a 2.5˚ grid and extend back to 1979. The dataset with monthly values is used here.

The global precipitation dataset developed by Adam et al. (2006) (*ADAM*) is based on a previous version of the Matsuura and Willmott database (Willmott and Matsuura, 2001). This dataset has been adjusted to correct for systematic wind induced undercatch and wetting losses from rain gauges (Adam and Lettenmaier, 2003) as well as for orographic effects (Adam et al., 2006). The combination of both adjustments resulted in a net increase of 17.9 % in global land precipitation, as compared to Willmott and Matsuura (2001). The monthly data is available on a 0.5° grid for 1979-1999.

First, the precipitation datasets are analyzed. For each basin determined by the validation stations (described in section 2.3), the mean annual precipitation for the overlapping period 1979-1999 is derived for all seven precipitation datasets:

$$P_{s,b} = \frac{1}{21} \cdot \frac{1}{A_b} \left(\sum_{y=1979}^{1999} \sum_{m=1}^{12} \sum_{c=1}^{n} P_{s,c,m,y} \cdot A_c \right) \quad (1)$$

where $P_{s,c,m,y}$ is the precipitation in dataset *s*, cell *c*, month *m* and year *y*, A_c is the area of cell *c*, A_b is the area of the basin *b* and *n* is the selection of cells that fall within the basin *b*. The *GPCP* and *CMAP* data are only available on a 2.5° grid, but were projected onto a 0.5° grid. No interpolation method was applied, but each 2.5˚ gridcell was divided in 25 gridcells of 0.5˚ with the same values.

The maximum mean annual precipitation per basin *b* is determined by

$$P\max_b = \max(P_{1,b},..,P_{7,b}) \quad (2)$$

and the minimum mean annual precipitation is derived analogously.

The absolute range in precipitation, representing the absolute uncertainty, is then given for each basin by

$$\Delta P_{abs,b} = P\max_b - P\min_b \quad (3)$$

and the relative range in precipitation, which is representing the relative uncertainty in precipitation, by

$$\Delta P_{rel,b} = 100 \cdot \frac{P\max_b - P\min_b}{P_{cru,b}} \quad (4)$$

The area weighted relative uncertainty is calculated as

$$\Delta P_{rel,weightedavg} = \frac{\sum_{b=1}^{294} (\Delta P_{rel,b} \cdot A_b)}{\sum_{b=1}^{294} A_b} \quad (5)$$

Subsequently the minimum and maximum of the mean annual precipitation calculations per basin are used to create the models' precipitation forcing. This is done by using the minimum and maximum values calculated in eq. 2 multiplied by the original *CRU* data for all basins:

$$P\max_{c,m,y} = \frac{P\max_b}{P_{cru,b}} \cdot P_{cru,c,m,y} \qquad (6)$$

The minimum precipitation forcing $P\min_{c,m,y}$ was created analogously.
The thus created input data cover the range in precipitation estimates per basin, but keep the spatial and temporal pattern of *CRU*. Two model runs were made to determine for each basin the resulting minimum and maximum simulated discharge.
For the uncertainty in seasonality of precipitation the same procedure was followed. For each precipitation dataset the mean seasonal (DJF, MAM, JJA, SON) precipitation for 1979-1999 was calculated for each basin. The minimum and maximum of those seasonal totals were used to scale the respective seasons of the *CRU* dataset.
It is not our aim to give a quality judgment on the precipitation data in this study. Therefore, the seven precipitation sets are given equal weight and the range of precipitation values derived from these sets is assumed to represent the uncertainty in precipitation.
Note that LPJmL is a dynamic vegetation model (see section 2.4), in which the spatial pattern of vegetation is closely linked to that of precipitation. To initialize the carbon and water pools, the model has been spun up for 1000 years by repeating the *CRU* climate of 1901-1930 before the transient simulations (see Sitch et al., 2003). In order to prevent that differences in simulated discharge between the runs arise from factors other than precipitation (e.g. the changed vegetation), we kept the spatial pattern of *CRU* and only used the precipitation totals derived from the other datasets.

Figure 2.1. Discharge stations used for validation and corresponding upstream areas.

2.2.2 Other climate input

Other meteorological variables that are used to force the model are monthly temperatures, the number of wet days per month and the average monthly cloud fraction per grid cell in order to calculate potential evapotranspiration. These variables are all taken from the *CRU* database (Mitchell and Jones, 2005; New et al., 1999; New et al., 2000) and are used for all simulations in this study.

2.2.3 Validation basins and data

There are several global gridded drainage direction maps (Döll and Lehner, 2002; USGS, 2000; Vörösmarty et al., 2000b). To compare the modeled discharge with the observations in a basin, it is important that the contributing area reported by the discharge measuring station matches the contributing area upstream of the station calculated by the river network. We therefore use the STN-30p network (Vörösmarty et al., 2000b) for accumulation and routing of computed runoff, and a subset of 663 discharge stations that were co-registered to this network (Fekete et al., 2000; Fekete et al., 2002). From these, we have analyzed the 294 most downstream stations of nested basins (figure 2.1; four basins were eliminated because their gauges fell outside of the LPJmL land mask). The area covered by these stations is approximately 70% of the world's actively discharging area (Fekete et al., 2002).

The 213 basins for which observation data are available (Global Runoff Data Centre, 2007) for at least 5 years within the 1979-1999 period are used to validate the model results with measured data.

2.2.4 Model description

We use the LPJmL ("Lund-Potsdam-Jena managed Land") dynamic global vegetation and water balance model (Bondeau et al., 2007; Gerten et al., 2004; Rost et al., 2008; Sitch et al., 2003) for the discharge simulations. LPJmL accounts explicitly for ecosystem processes such as establishment, growth and mortality of potential natural vegetation. In contrast to global hydrological models, it does not use a prescribed natural vegetation pattern but it dynamically computes (changes in) natural vegetation patterns from soil properties and climate. The vegetation competes for resources (water and light). The model calculates the full carbon and water balances, which are coupled e.g. through photosynthesis.

The LPJmL model uses a 2-layered soil, with a top layer of 0.5 m and a second layer of 1 m thickness. The soil water balance is calculated daily, including precipitation, snowmelt, interception loss, soil evaporation, transpiration, percolation and runoff. The total runoff is calculated as the sum of surface runoff from the first soil layer, subsurface runoff from the second soil layer and water percolating through the second soil layer. The surface and subsurface runoff are defined as the excess water above field capacity of the first and the second soil layer.

Subsequently the runoff water is routed through the above-described gridded network with a constant velocity of 1 ms^{-1}.

Gerten et al. (2004) evaluated the water balance of an earlier version of the model for a small set of basins and concluded that the model results for runoff and evapotranspiration agree well with the results reported by state-of-the-art global hydrological models. However, all models in that analysis showed systematic bias in many regions, e.g. an overestimation in dry regions and an underestimation especially in high latitudes. Recently, LPJmL has been extended with a representation of prescribed agricultural land (Bondeau et al., 2007) as well as a routing (including lakes) and irrigation scheme (Rost et al., 2008). This latter version is used here, though the irrigation module was switched off.

2.3 Results

2.3.1 Precipitation

2.3.1.1 Mean annual precipitation

At the global scale, the seven precipitation datasets differ considerably in their global totals, though their inter-annual variability is largely similar (figure 2.2). The *ADAM* dataset gives substantially higher total land precipitation than the others, followed by *GPCP*. This can be explained by the application of correction factors for high elevation and snow dominated areas in these datasets. The mean annual land precipitation estimates vary from 96286 to 118006 km^3 yr^{-1} (743 to 926 mm yr^{-1}) for the years 1979-1999.

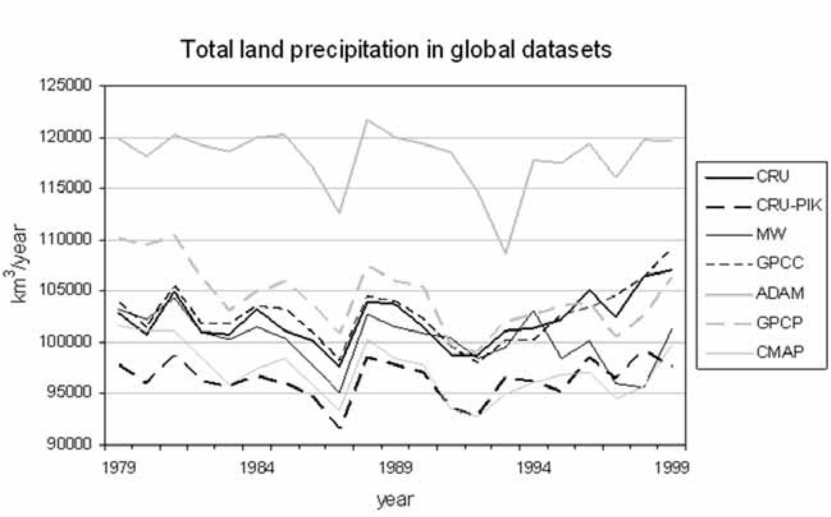


Figure 2.2. Total land precipitation (km^3 $year^{-1}$) for 7 global precipitation sets 1979-1999. Only cells that are common in the 7 sets are taken into account.

2.3.1.2 Mean annual precipitation per basin

Figure 2.3 shows the *CRU* mean annual precipitation as well as the relative range between the seven datasets for all basins (as Eq. 4). Although the largest absolute ranges can be seen in basins that have high precipitation (not shown in a figure), it is obvious from figure 2.3b that the largest relative ranges between the precipitation sets are found in mountainous, arctic and small catchments. This large uncertainty in precipitation in mountainous and arctic regions can be explained by the correction factors that have been applied in some data sets (*ADAM* and *GPCP*). The relative large ranges in small basins might be caused by the fact that variations between the datasets in the spatial distributions of precipitation are relatively more important for small basins, where it can be essential whether precipitation falls in a particular cell or a neighboring cell outside of the basin. In larger basins, those differences are more likely to average out over the total area. The weighted average precipitation range (eq. 5) per basin is 30%.

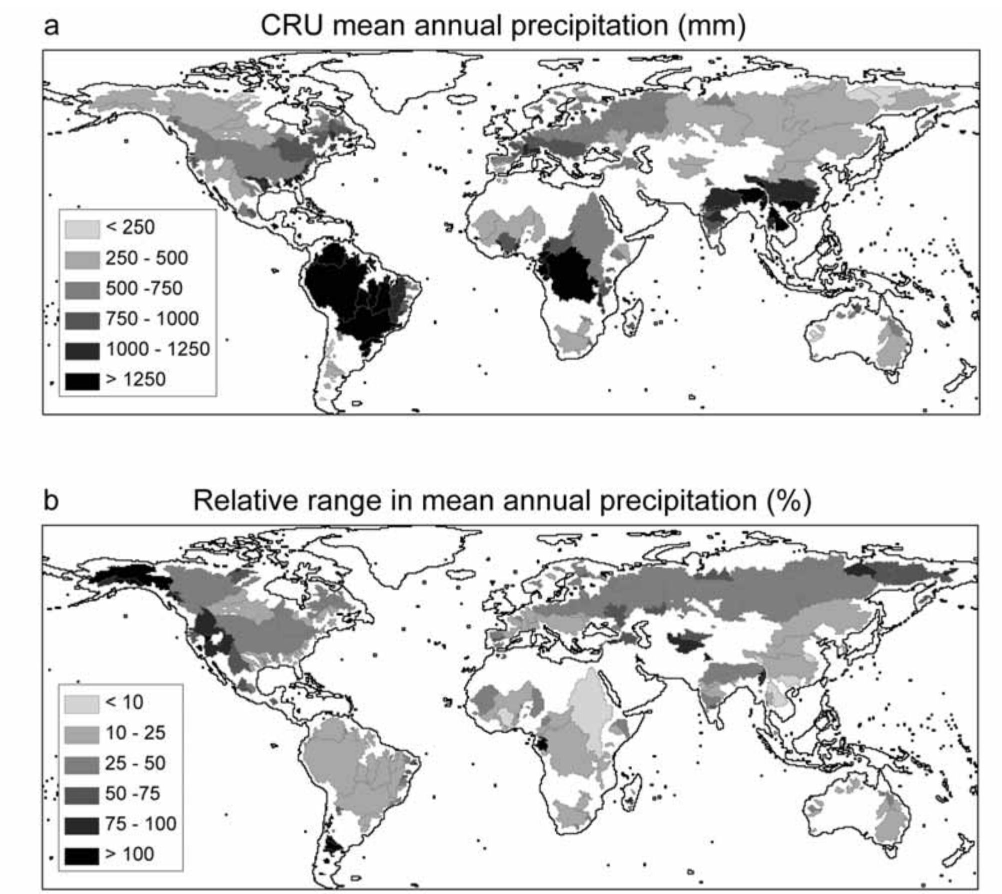


Figure 2.3. a. *CRU* mean annual precipitation per basin in mm year^{-1} (1979-1999); b. the range in mean annual precipitation between the 7 datasets per basin, in % of the *CRU* mean annual precipitation.

2.3.1.3 Seasonality in precipitation per basin

The absolute ranges in precipitation (derived as in equation 3, but with mean seasonal precipitation) per basin were found to be season dependent and to occur mainly in the wettest seasons (figure not shown). The mountainous, arctic and small basins again show the largest relative ranges in precipitation in all seasons. Furthermore, the relative ranges in precipitation are largest in the Nordic basins (in the US, Canada, Russia, Northern Europe and Northern China) in winter. This is as expected, because in this season most precipitation falls as snow, which is more difficult to measure (Adam et al., 2006). In *ADAM* and *GPCP*, a snow undercatch correction has been applied, which additionally explains the large variation among the different datasets. In summer the relative ranges are lower in those basins. For the other basins, the relative ranges in precipitation are more or less constant over the year.

Figure 2.4 presents the ranges in mean monthly precipitation for 16 basins (see locations in figure 2.1). It can be concluded from these graphs, as well as for the other 278 basins not shown here, that the differences between the precipitation datasets are caused by a relative shift in total precipitation. The patterns of monthly precipitation distribution are similar (see also online database). There are no datasets that report the same mean annual precipitation

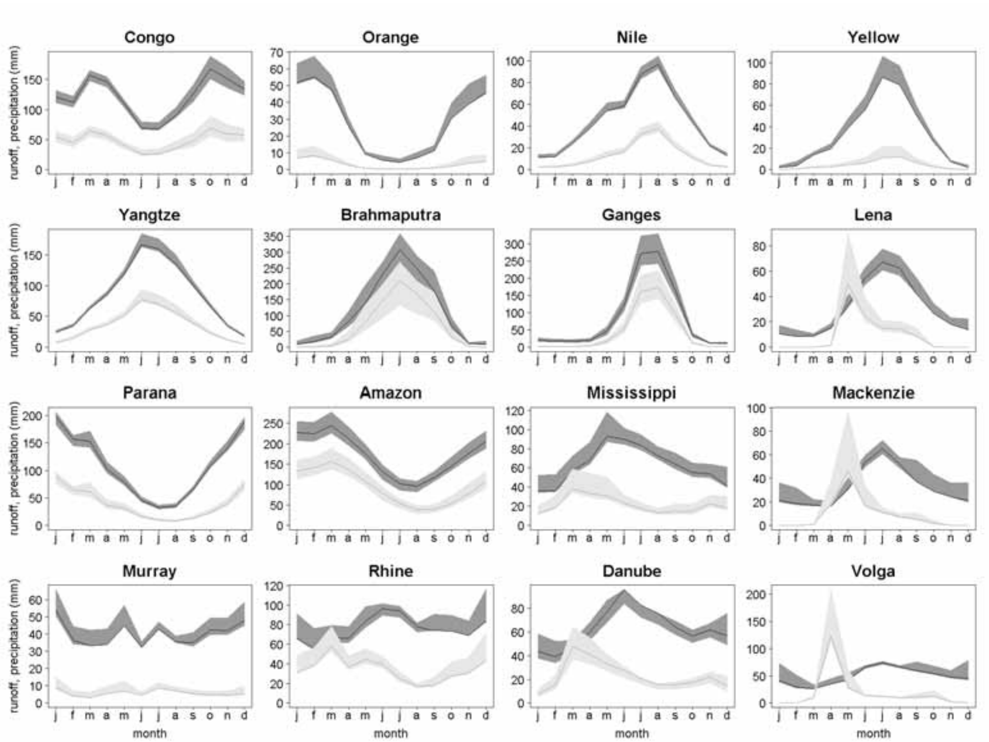


Figure 2.4. Uncertainty in mean monthly precipitation (dark grey) and resulting uncertainty in runoff (light grey) for selected river basins (both in mm month^{-1}). The solid lines show the CRU mean monthly precipitation and the LPJmL-simulated runoff with *CRU* input.

values, but show a completely different distribution throughout the year. This can probably be explained by the fact that all datasets are partly based on the same station data and the differences are caused by the interpolation and correction method applied and the additional sources used. The bias between the datasets cannot be traced back to one particular season, except for the basins where an undercatch correction has been performed. These basins show a relative higher precipitation uncertainty in the winter season compared to other seasons (e.g. in Mackenzie and Volga).

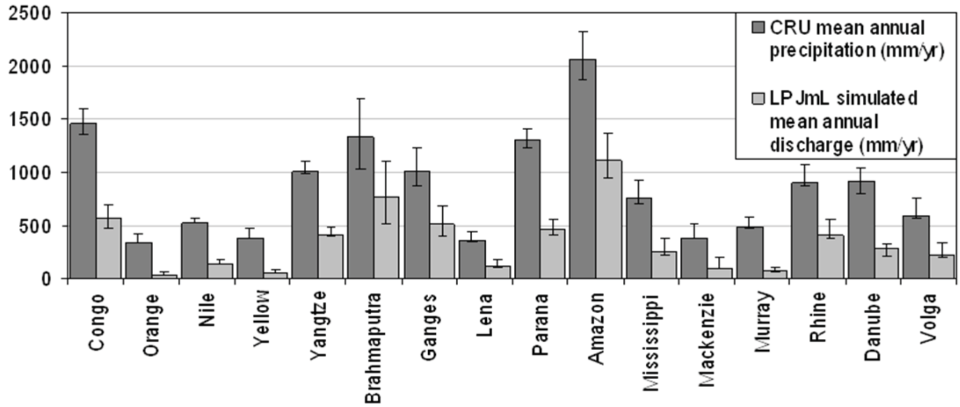


Figure 2.5. *CRU* mean annual precipitation and resulting LPJmL-simulated discharge. The error bars represent the ranges in precipitation as derived from the 7 datasets and the resulting ranges in discharge simulations.

2.3.2 Discharge

2.3.2.1 Mean annual discharge per basin

Figure 2.6a shows the mean annual discharge simulated by LPJmL forced with *CRU* precipitation. From figure 2.5 and 2.6b it is clear that ranges in precipitation (figure 2.3) translate into similar patterns of ranges in discharge, but with higher relative numbers (compare figure 2.3b with figure 2.6b). Large uncertainties in discharge can be seen in northern basins in Europe, Asia and North America and in the mountainous and small basins. The area weighted average uncertainty (as equation 5, but with discharge values) in the mean annual discharge calculations is 90%, and thus is three times higher than the average uncertainty in precipitation.

Figure 2.6c and d illustrate the basins' sensitivity to precipitation uncertainty. Figure 2.6c shows the fraction of precipitation uncertainty that results in runoff uncertainty. In regions where this fraction is high, the absolute uncertainty in discharge is almost the same as the absolute uncertainty in precipitation. Physically this means that in those areas the evaporative demand is largely met and the soil is very moist, causing extra precipitation to add to runoff immediately. Basins in the tropics and in high latitudes show a higher fraction than basins in temperate regions.

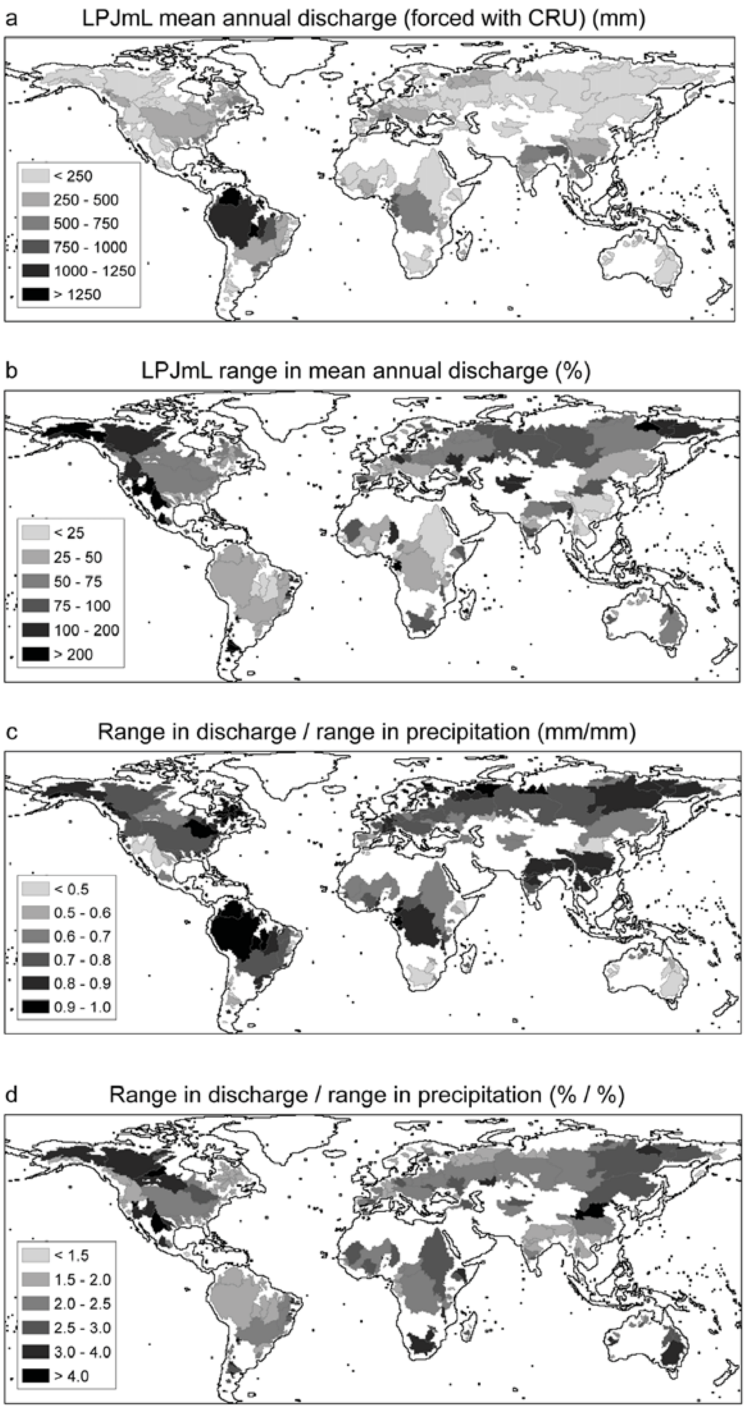


Figure 2.6. (a). Mean annual discharge per basin as calculated by LPJmL based on *CRU* input (b). relative range in LPJmL discharge calculations resulting from ranges in precipitation estimates (c) absolute range in discharge over absolute range in precipitation (d) relative range in discharge over relative range in precipitation.

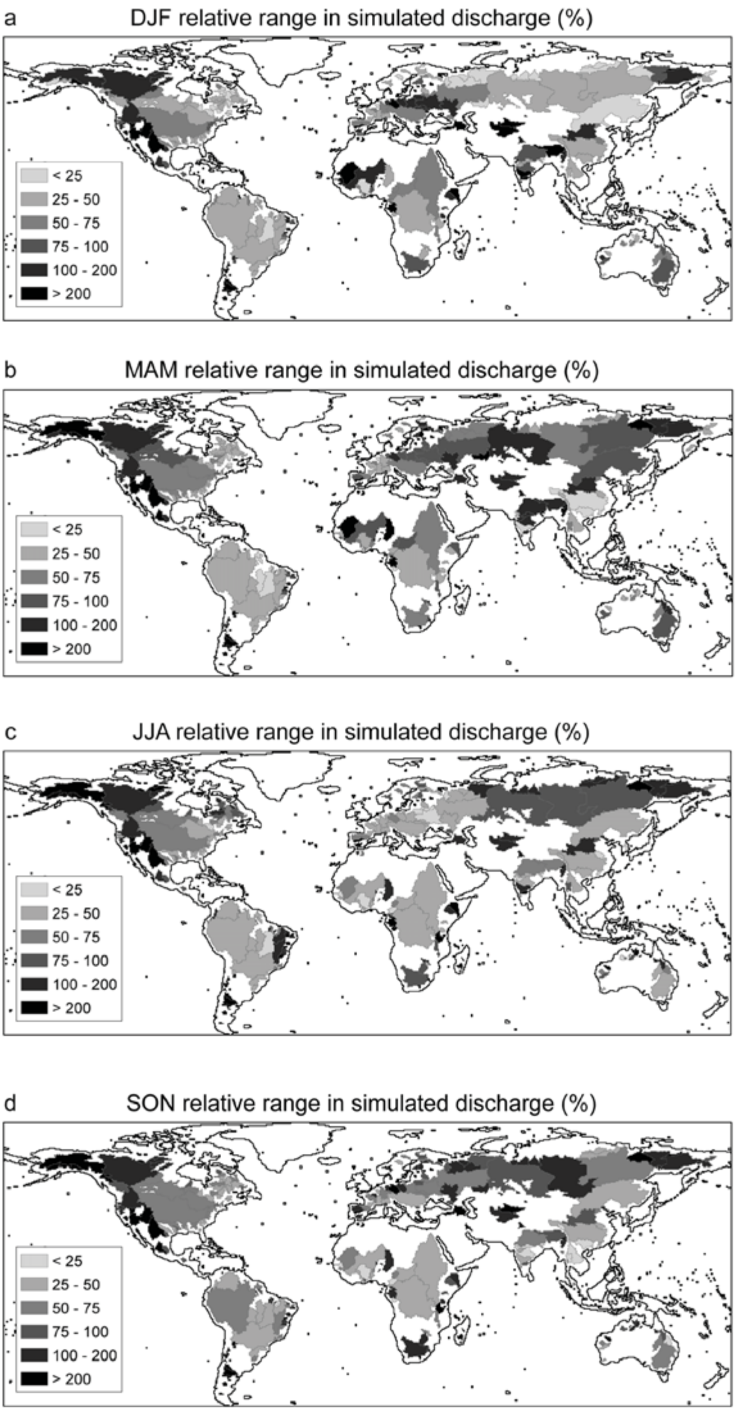


Figure 2.7. Relative ranges in discharge simulations per season as percentage of the discharge simulated with *CRU* precipitation.

In relative terms, however, for almost all basins the relative discharge uncertainty is larger than the relative uncertainty in precipitation (if sensitivity >1 in figure 2.6d). This implies that the relative precipitation uncertainty is amplified in the discharge calculations.

2.3.2.2 Seasonality in discharge

As expected, the basins that have a large uncertainty in the precipitation input also have a large resulting uncertainty in the estimated discharge in each season (Figure 2.7a-d). However, there are some clear seasonal differences. In Europe, the relative uncertainty in summer discharge is lower than in winter, although absolute precipitation is larger in summer. In high latitude basins the uncertainty in winter discharge is low, although the precipitation uncertainty is high in this season. The uncertainty in precipitation input leads to ranges in discharge of more than 75% in those high latitude basins, except in winter (figure 2.7a).

In general, for all basins the precipitation uncertainty is translated into discharge uncertainty (Figure 2.4). However, the largest uncertainty in precipitation and discharge do not always occur at the same time (Figure 2.8a-d). In northern basins, the uncertainty in winter precipitation does not directly translate into a range in discharge. During the winter months the precipitation is stored in the snowpack and only released as discharge in spring or summer. Large basins like the Nile and the Amazon also show a shift of the uncertainty signal in time, because of the time the water needs to reach the outlet of the river.

2.3.3 Validation with observed discharge data

Figure 2.9a suggests that the LPJmL model produces too little streamflow in the high latitudes and too much streamflow in the tropical and some mid latitude basins. Assuming reliable input and validation data, it can be concluded that model calibration is necessary to compensate for the over- and underestimations, or that some processes need a better representation.

However, as shown in the previous sections, the precipitation input is very uncertain and before validation and calibration of the model, the uncertainties in streamflow caused by the input uncertainties should be taken into account. When forcing the model with the minimum and maximum of precipitation for each basin, we attain for 95 out of 213 of basins that the observed discharge falls within the ranges of uncertainty of the simulated discharge. For another 23 basins, the difference between the observed and closest simulated discharge is less than 10% (figure 2.9b). For tropical basins in Africa and the Mississippi basin, the model still tends to overestimate the streamflow compared to observations, even after accounting for the uncertainty in precipitation. However, it should be noted that that these overestimations are probably caused by the fact that neither evaporation from the stream nor water extraction for irrigation are taken into account in the model run, which are both very high in those basins. Figure 2.10 shows for the individual seasons that by accounting for the precipitation uncertainty

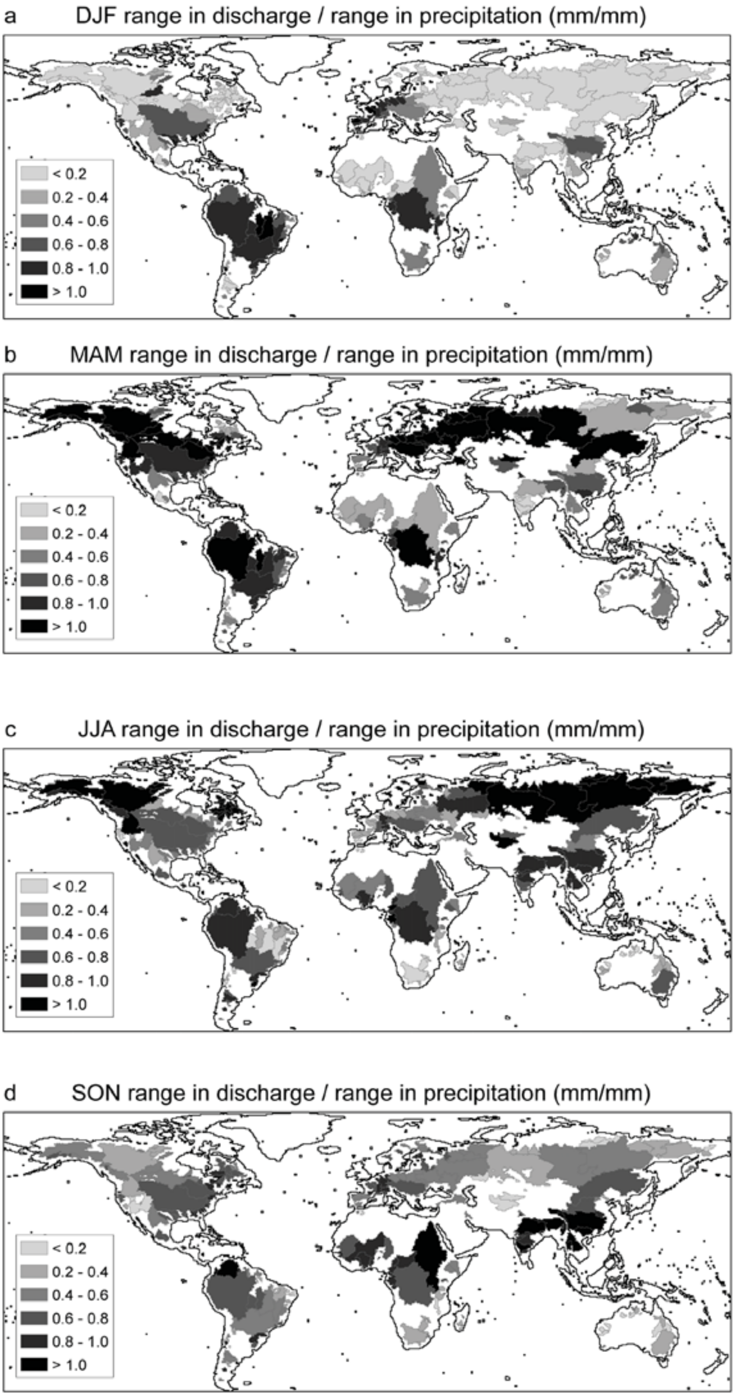


Figure 2.8. Discharge uncertainty (mm) divided by precipitation uncertainty (mm) for each season.

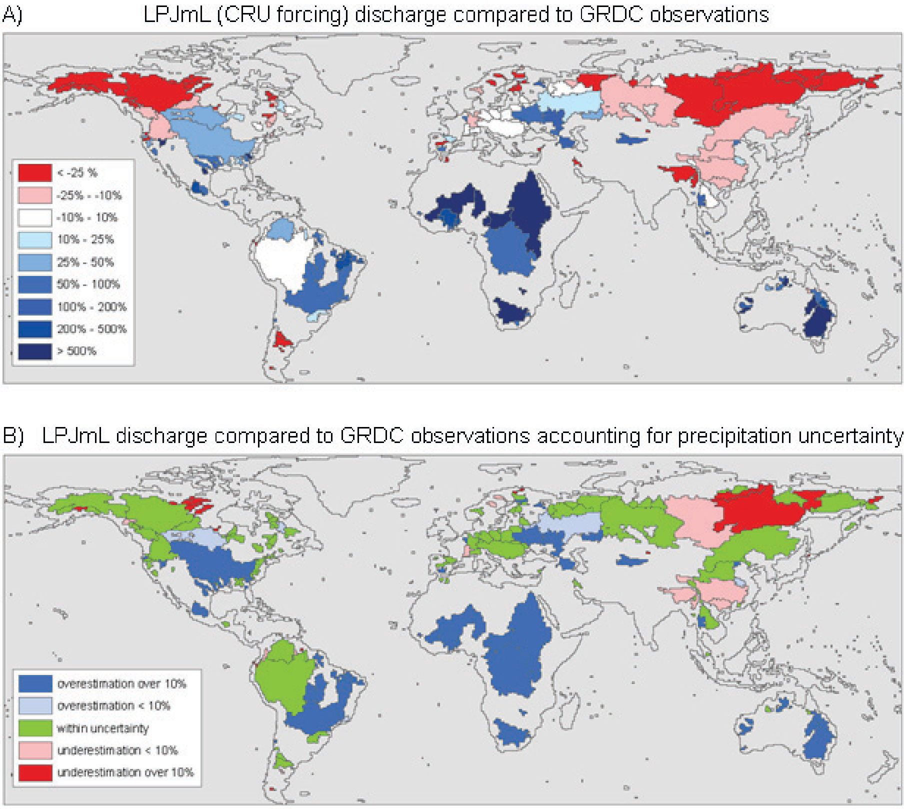


Figure 2.9 a. Percent differences between LPJmL estimations of discharge based on *CRU* climatic forcing and GRDC streamflow observations. b. Basins for which the observed discharge lies either within or outside of the simulated range under the different precipitation datasets.

the observed value can often be captured, while the model would fail more often when using a single precipitation set (*CRU*). However, there are some seasonal differences, in that the performance is somewhat better in spring and autumn months, as compared to the other seasons.

2.3.4 Additional results

The model runs and the analysis have been done for all basins shown in figure 2.1. For researchers with particular interest in specific basins, those results can be consulted online (www.climatexchange.nl/projects/JHM). The website contains a database with information on the inter-annual as well as intra-annual variations in precipitation in each river basin as derived from the described global precipitation datasets. The resulting ranges in discharge are calculated with the LPJmL model and compared with GRDC observations if available.

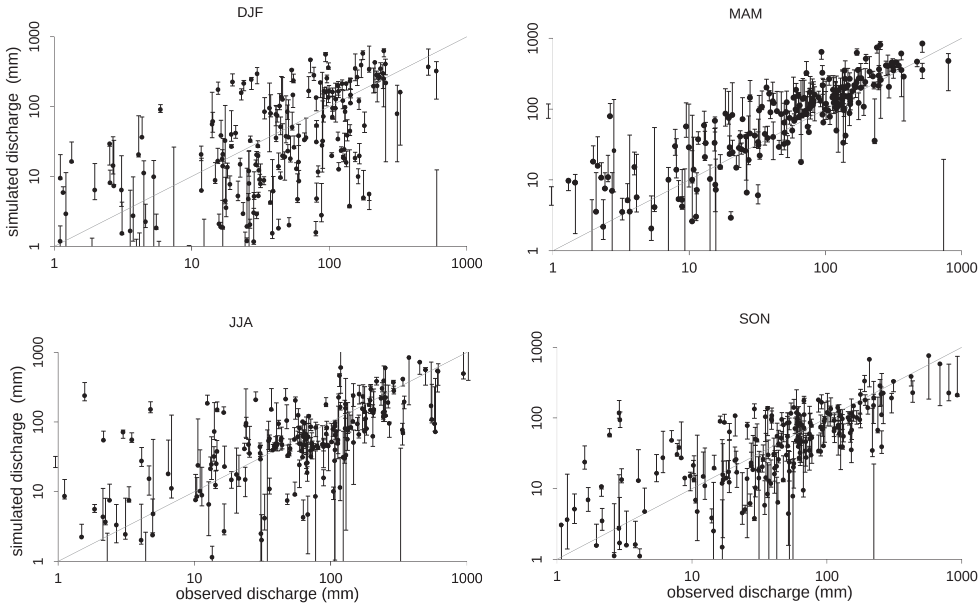


Figure 2.10. Observed discharge versus range in simulated discharge for the four seasons and the 213 river basins (error bars: range; dots: values under *CRU* precipitation input).

2.4 Discussion and conclusions

The comparison of seven global gridded precipitation datasets on a basin scale results in absolute and relative ranges in mean annual precipitation. The absolute total and relative differences in precipitation between the datasets found here at basin scale are typically lower than those found for the grid scale (the latter is analyzed by Fekete et al., 2004). This is because a lot of spatial differences between the datasets are averaged out when summed over a larger area. However, at the basin scale the precipitation estimates still differ a lot for some basins, especially in mountainous areas, where precipitation measurement errors are large and spatial interpolation is more difficult, and at high latitudes, where datasets not corrected for systematic wind induced undercatch tend to underestimate the total precipitation (Adam and Lettenmaier, 2003). Areas with low precipitation uncertainty typically have simpler topography, are not snow dominated and have a dense precipitation network. Furthermore, the precipitation datasets follow the same seasonality pattern, so that the main differences are in total rather than in temporal distribution of the precipitation. Exception to this pattern occurs in high latitude basins, where the uncertainty in the snow dominated winter season is larger than in the other seasons.

Our results show that the uncertainty in precipitation has a significant impact on discharge estimations. Typically, the uncertainty in precipitation propagates in larger relative uncertainty in discharge calculations. Although the relative precipitation uncertainty does not change a lot during the year, the resulting discharge uncertainty does sometimes show seasonal differences. In regions where the precipitation is stored as snow in winter and released as runoff in spring, the uncertainty in winter and spring precipitation is added up to a large discharge uncertainty in spring.

This quantification of the large uncertainty in discharge calculations resulting from precipitation input uncertainty is important for hydrological modelers who estimate current or future water resources, as for example to be conducted in the EU project WATCH (www.eu-watch.org). It makes proper validation ambiguous and calibration difficult. Most current model calibration strategies ignore this input uncertainty and estimate the models parameters based on one precipitation dataset as if the precipitation was known exactly (e.g. Döll et al., 2003; Nijssen et al., 2001), possibly leading to wrong parameter estimates and simulation results (Kavetski et al., 2002; Vrugt et al., 2005).

The discharge estimations as simulated by the LPJmL model show that including precipitation uncertainty results in a discharge uncertainty that overlaps the observed value in 95 out of 213 basins. For 23 basins the observed discharge differs less than 10% from the simulated range. Under the assumption that all precipitation datasets have the same quality, and their range reflects the uncertainty, for these basins a calibration cannot improve the model results. For the other basins, where forcing the model with the different precipitation sets lead in all cases to an under- or overestimation, a calibration could improve the simulated discharge. However, it is also possible that missing processes are causing the under or overestimations. For example for African basins, the observed overestimation can be explained by the evaporative losses from the stream and irrigation extractions that are not represented by the model.

Because calculated discharge is to such a large extent depending on uncertain input data, it might not be useful to calibrate a model with one particular dataset. This would give a false impression of the performance of the model. After calibration, the model seems to a large extent able to reproduce the observed discharge in river systems over the world. However, using a different input dataset gives other model results, thus using a different input dataset to calibrate the model on, could possibly lead to very different calibration parameters, and therefore different hydrological behavior of the model.

There are three possible approaches to account for this uncertainty in global hydrological modeling (schematically illustrated in figure 2.11) to be used for future projections. Because the precipitation datasets do not differ in their representation of seasonality, these simple approaches are justified.

The first possible solution (1) would be to calibrate the model on multiple datasets to find the possible parameter space for the calibrated parameters. This parameter space could then subsequently be used to project future water resources as a range instead of a single number.

Instead of performing a calibration 7 times, the precipitation coefficients in table 2.2 can be used to obtain the range in precipitation estimates for each basin. The coefficients reflect the uncertainty in precipitation amongst 7 datasets relative to *CRU*, and can be applied to scale the *CRU* dataset. The parameter space can then be obtained by performing 2 calibrations, one on the resulting maximum and one on the minimum dataset. Another way to explicitly disaggregate different sources of uncertainty in model calibration is developed by Vrugt et al. (2005) and Kavetski (2006a). Kavetski et al. (2006a) developed a method (Bayesian total error analysis) to account for input uncertainty in model calibration and applied this method to a hydrological model on catchment scale (Kavetski et al., 2006b). To our knowledge, no global hydrological model has been calibrated in this way and it requires further research to explore the applicability of this method to a global hydrological model.
A second option (2) is not to calibrate, but use the current model parameters and the uncertainty in precipitation to project water resources. It requires that the model parameters have a physical meaning and can be estimated from existing literature. Models that use physical parameters and have not been calibrated are MacPDM (Arnell, 1999b), WBM (Vörösmarty et al., 1998) and the here used LPJmL. To estimate the impact of precipitation uncertainty on discharge at least two model runs have to be performed, respectively with minimum and maximum estimates of precipitation. Because we have shown that the datasets show the same distribution of precipitation in time, the *CRU* data and precipitation coefficients derived in this study (table 2.2) can be used. The minimum and maximum precipitation datasets can be obtained by multiplying the *CRU* values with the coefficients in table 2.2 for the required basins, as is done in this study.

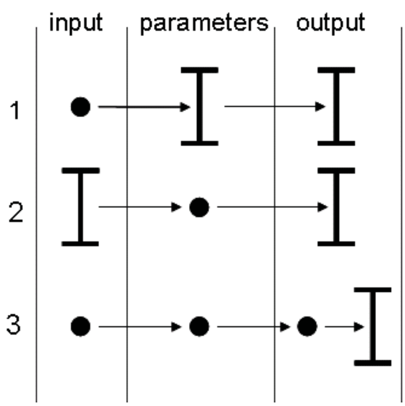


Figure 2.11. Schematic presentation of three approaches to estimate the uncertainty in model output. The I shows when ranges are applied. 1. Use of one forcing set with multiple model parameter settings to estimate the uncertainty in output 2. Multiple forcing data are used with a single model to estimate the uncertainty in output (as done in this study). 3. The model is run with single forcing and a single parameter set and the uncertainty is estimated afterwards.

A third option (3) is to apply the results from the analysis presented in this paper in discharge estimations as uncertainty bands. Under the assumption that using another model for this analysis would not significantly change the results, the basin uncertainty estimations for discharge can be obtained by multiplying the model results with the coefficients in the last columns of table 2. These coefficients can be applied to any model result to present the uncertainties in discharge resulting from precipitation uncertainty, on condition that the model has been run forced with *CRU* precipitation data. The advantage of this option is that only one model run is required, and the uncertainty in results is estimated as a post-processing procedure.

A general conclusion of this paper is that a deterministic approach, such as it is often used in water resources research, is too simplistic. The range of uncertainty in input data has a large influence on the output and may not be neglected in the communication of results. This is even more true when modeling water resources under climate change, because the uncertainty in future precipitation produced by different climate models is even larger than the uncertainty in historical data (Meehl et al., 2007). Therefore, it would be better to change to a probabilistic way of presenting results and projections of future water resources.

In this study we have chosen to give no quality judgment of the precipitation datasets and give them equal weight in the analysis. An additional study could maybe reduce the precipitation uncertainty by eliminating the datasets that are known to be of less quality. However, this study clearly shows the need for more accurate precipitation datasets to be used for forcing hydrological models.

Acknowledgements

This research was supported by the Strategic Research Programme Climate Change (KB2, 2008-2010) of the then Dutch Ministry of Agriculture, Nature and Food Quality, by the European Union (FP6) funded projects WATCH (Grant nr. 36946) and SCENES (Grant nr. 36822), and by the Netherlands Environmental Assessment Agency (PBL). The authors would like to thank three anonymous reviewers for useful comments on an earlier version of this paper. The Global Runoff Data Center is acknowledged for the provision of global discharge data..

Table 2.2. Overview of the precipitation uncertainty analysis for selected basins. Results of the analysis for other basins can be found on the website.* Values in these columns are basin specific multiplication factors for precipitation and resulting discharge calculations. Uncertainty in precipitation and discharge can be estimated by multiplying the factors with *CRU* precipitation data and *CRU*-forced discharge.

		mean annual precipitation 1979-1999 (mm yr^{-1})					mean annual discharge 1979-1999 (m^3 s^{-1})				
River	**station name**	**cru**	**min**	**max**	**min***	**max***	**cru forcing**	**min**	**max**	**min***	**max***
Congo	Kinshasa	1454	1349	1602	0.93	1.10	65068	54738	79820	0.84	1.23
Orange	Vioolsdrif	332	332	415	1.00	1.25	855	858	1647	1.00	1.93
Nile	El Ekhsasa	523	523	565	1.00	1.08	16708	16708	20076	1.00	1.20
Yellow	Huayuankou	383	383	470	1.00	1.23	1104	1106	2129	1.00	1.93
Yangtze	Datong	1002	988	1096	0.99	1.09	22465	21782	26871	0.97	1.20
Brahmaputra	Bahadurabad	1332	1035	1694	0.78	1.27	13614	8967	19500	0.66	1.43
Ganges	Farakka	1012	873	1222	0.86	1.21	15283	11900	20522	0.78	1.34
Lena	Stolb	361	349	443	0.97	1.23	8548	7866	13662	0.92	1.60
Parana	Corrientes	1303	1225	1413	0.94	1.08	32212	27985	38408	0.87	1.19
Amazon	Obidos	2057	1878	2329	0.91	1.13	164630	140931	201771	0.86	1.23
Mississippi	Vicksburg	749	710	925	0.95	1.23	23746	21128	36339	0.89	1.53
Mackenzie	Arctic Red River	387	378	512	0.98	1.33	4863	4590	10030	0.94	2.06
Murray	Lock 9 upper	481	472	573	0.98	1.19	2069	1959	3322	0.95	1.61
Rhine	Rees	906	870	1077	0.96	1.19	2083	1933	2829	0.93	1.36
Danube	Ceatal Izmail	759	675	825	0.89	1.09	6869	5387	8114	0.78	1.18
Volga	Volgograd Power Plant	587	570	750	0.97	1.28	9261	8730	14740	0.94	1.59

* Values in these columns are basin specific multiplication factors for precipitation and resulting discharge calculations. Uncertainty in precipitation and discharge can be estimated by multiplying the factors with CRU precipitation data and CRU-forced discharge.

3

Impact of reservoirs on river discharge and irrigation water supply during the 20th century

This paper presents a quantitative estimation of the impact of reservoirs on discharge and irrigation water supply during the 20th century at global, continental and river basin scale. Compared to a natural situation the combined effect of reservoir operation and irrigation extractions decreased mean annual discharge to oceans, and significantly changed the timing of this discharge. For example in Europe, May discharge decreased by 10%, while in February it increased with 8%. At the end of the 20th century, reservoir operations and irrigation extractions decreased annual global discharge by about 2.1% (930 km^3 $year^{-1}$).
Simulation results show that reservoirs contribute significantly to irrigation water supply in many regions. Basins that rely heavily on reservoir water are the Colorado and Columbia basins and several large basins in India, China and Central Asia (e.g. in the Krishna and Huang He, reservoirs more than doubled surface water supply). Continents gaining the most are North America, Africa and Asia where reservoirs supply respectively 57, 22 and 360 km^3 $year^{-1}$ between 1981-2000, which is in all cases 40% more than the availability in the situation without reservoirs.
Globally the irrigation water supply from reservoirs increased from around 18 km^3 $year^{-1}$ (5% more surface water) at the beginning of the 20th century to 460 km^3 $year^{-1}$ (almost adding 40% to surface water supply) at the end.
The analysis is performed using a newly developed and validated reservoir operation scheme within a global-scale hydrology and vegetation model (LPJmL).

Based on:

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R.W.A. Hutjes, J. Heinke, W. von Bloh, D. Gerten (2011). Impact of reservoirs on river discharge and irrigation water supply during the 20th century. Water Resources Research, Volume 47

3.1 Introduction

Water is an essential resource for life on earth. Due to population and economic growth global water demand will continue to increase in the near future. At the same time, climate change will alter the global water cycle, reducing water availability in critical locations (see Bates et al., 2008; Kabat et al., 2004). For centuries people have been intervening in the natural water cycle to make more water available for anthropogenic use. Irrigation systems have made dry areas suitable for agricultural production, and reservoirs were built for multiple purposes: to use the energy potential of rivers for electricity production, to reduce discharge variability for improved navigation, or to supply water for irrigation and other users (ICOLD, 2007; WCD, 2000). Most profound changes that humans have made to the hydrological cycle took place in the 20th century. The total global irrigated area has increased from around 40 Mha in 1900 to 215 Mha in 2000 (Fader et al., 2010) and the total cumulative storage capacity of large dams has increased from less than 100 km^3 in 1900 to around 8,300 km^3 in 2000 (Chao et al., 2008; ICOLD, 2007).

Current estimates of the total global annual water demand for irrigation around the year 2000 range from 1,900 to around 3,800 km^3 $year^{-1}$ (Döll and Siebert, 2002; Rost et al., 2008 and the references therein; Vörösmarty et al., 2005; Wisser et al., 2008), depending to a large extent on the datasets used for irrigated area and climate (Wisser et al., 2008) . Gerten et al. (2008) have estimated that expansion of irrigation has decreased global river discharge to the oceans by 0.3 % (equaling 118 km^3) between 1901 and 2002, with pronounced regional effects including regional increases due to increased return flows to the river system.

Nilsson et al. (2005) showed that currently over half of the world's global river systems are regulated by dams, which mostly lie in basins where irrigation and economic activities take place. The total cumulative storage of large dams is about 20% of global annual runoff (Vörösmarty et al., 1997). However, there are large regional differences: in the US, for example, the total storage capacity of large dams is more than 75% of the mean annual runoff (Graf, 1999). The global standing pool of rivers has increased seven-fold as compared to a situation without artificial reservoirs (Vörösmarty et al., 1997), and consequently reduced global sea level rise by 30 mm (Chao et al., 2008). For African countries, a correlation has been found between the storage capacity of the country and its economic development (Ludwig et al., 2009).

In addition to the positive effects that large infrastructural water project like dams can have on water supply for different sectors and on flood risk reduction, there are also negative effects. These negative effects include alteration of the natural river dynamics of water, sediments and nutrients, habitat fragmentation and loss of biodiversity (Graf, 2006; Poff et al., 2007; Rosenberg et al., 2000; Syvitski et al., 2005; Vörösmarty et al., 2003).

In the assessment of current and future water resources it is important to account for large reservoirs and their impact on water availability for different sectors (e.g. Biemans et al., 2006). The available water resources for human use, and potential (future) water stress, can be evaluated only when human alterations to the hydrological cycle are taken into account. However, only a few global water resources assessments have accounted explicitly for the operation of large reservoirs. On the continental and global scale those studies have mainly focused on the influence of dams on discharge patterns (Döll et al., 2009; Haddeland et al., 2006b; Hanasaki et al., 2006). At basin scale, especially in the United States, information on the management of dams is readily available, making it possible to simulate the impact of dams on river systems in more detail (see e.g. Christensen et al., 2004; Graf, 2006; Payne et al., 2004). Also for basins outside of the U.S., studies exist on the influence of dams on discharge in specific river basins (Adam et al., 2007; Yang et al., 2004; Yang et al., 2008; Ye et al., 2003).
The potential contribution of rainwater harvested in small local reservoirs to global irrigation supply has been quantified to range between 1,847 to 2,511 $km^3 yr^{-1}$ by Wisser et al. (2010). However, the contribution of large reservoirs to irrigation has to our knowledge never been quantified at the global scale before.
The objective of our research was to estimate the impact of large reservoirs on water availability and irrigation water supply during the 20th century. Therefore, a reservoir operation scheme has been developed within the dynamic global vegetation and hydrology model LPJmL. All analyses were performed at global, continental and river basin scale, focussing both on the increasing impact of reservoirs during the 20th century and on the intra-annual dynamics during the last part of the 20th century.

3.2 Methods

3.2.1 LPJmL

The LPJmL model is designed to simulate the global carbon and water balances in conjunction with the dynamics of natural and agricultural vegetation. It runs at 0.5 degree spatial resolution at daily time steps. Originally the model was developed as a dynamic global vegetation model (LPJ), simulating changing patterns of potential natural vegetation based on soil properties and climate (Gerten et al., 2004; Sitch et al., 2003). In recent years, the model has been extended to LPJmL, which includes a dynamic representation of cropland and grazing land in order to simulate the growth, production and management regime of the world's major crop types (Bondeau et al., 2007; Fader et al., 2010), as well as a global routing and irrigation module (Rost et al., 2008). The river routing and irrigation module has been efficiently implemented on a parallel cluster speeding up the simulations (von Bloh et al., 2010). LPJmL has been systematically validated against discharge observations for 300 globally distributed river basins (Biemans et al., 2009, chapter 2) and against irrigation water use and consumption (Rost et al., 2008).

For each crop LPJmL calculates a growing season which is defined as the period between sowing date and harvest date. Once a year, sowing dates are determined as a function of climate and crop specific thresholds regarding temperature and/or precipitation. Sowing dates determined by temperature (temperate cereals, sunflower and rapeseed) are modelled based on the 20 years previous' average date on which temperature drops below (for winter types) or rises over (for spring types) a crop-specific threshold value. Sowing dates determined by precipitation (tropical cereals, tropical roots and groundnut) require 40 mm (110 mm in tropical Asia) of precipitation accumulated over the previous 10 days. For maize, the temperature and/or precipitation threshold depends on the latitude. For rice, pulses, temperate roots and soybean the sowing dates are fixed. Phenological development towards maturity is modelled using heat unit theory and harvest occurs as soon as maturity is reached. Rice is assumed to grow twice a year in tropical Asia (for more details, see Bondeau et al., 2007).

The irrigation algorithm is described in detail by Rost *et al.* (2008). Irrigation only occurs during the growing season. The net irrigation demand of an agricultural field is defined as the amount of water needed to either fill the soil to field capacity, or the amount needed to fulfil the atmospheric evaporative demand. The gross water demand is determined by multiplying the net irrigation demand with a country-specific efficiency factor, which depends on the irrigation system (estimated by Rohwer et al., 2007). This gross irrigation demand is first fulfilled by taking water from the cell's lakes and rivers. Second, if the local cell cannot fulfil the demand, water is taken from the adjacent grid cell with the highest discharge. Third, in the expanded LPJmL containing the reservoir module (described below), if there is still a remaining irrigation demand, water is requested from the reservoir. The reasoning behind this assumption is that it is probably easier and cheaper for farmers to access their locally produced runoff or to use a local river than to be supplied from a reservoir. Fourth, if irrigation supply is assumed not to be restricted by availability of renewable water, the remaining demand can be filled up assuming unlimited supply (e.g. from fossil groundwater). Figure 3.1 illustrates the irrigation algorithm.

Not all the water that is extracted reaches the agricultural fields, and transport losses are accounted for by applying a country-specific conveyance efficiency factor. The conveyance efficiency varies between 0.7 to 0.95 depending on the irrigation system used (open canals or pipeline systems) (see Rohwer et al., 2007; Rost et al., 2008). 50% of the water lost during conveyance is assumed to evaporate and 50% is assumed to return to the river.

3.2.2 Reservoir module

For this study, the LPJmL model has been extended with a new reservoir module and an expanded irrigation module, affecting the seasonal timing of discharge and the amount of water locally available for irrigation.

Since there is no global dataset on the management of dams, it was necessary to develop a generic reservoir operation model based on known functions of the reservoir. Until now two reservoir operation schemes used in large scale hydrological models have been described. Haddeland et al. (2006b) developed an optimization algorithm, in which information regarding inflow, downstream water demand and reservoir evaporation is used to optimize reservoir outflow, depending on the purposes of the reservoir. The algorithm has been tested and applied for North America and Asia (Haddeland et al., 2007). The advantage of this scheme is that it simulates the operation of reservoirs with different purposes (irrigation, hydropower, flood protection, water supply/navigation), and it can take into account multi-purpose reservoirs. Further, it simulates not only reservoir outflow, but also extractions from reservoirs for irrigation during water scarce periods, based on estimated irrigation demand. Irrigation efficiency and conveyance losses are not taken into account. Furthermore, in this scheme the optimization algorithm is applied retrospectively (Haddeland et al., 2006b), which means that it uses information on river flow and water demand for the whole operational year in a post-processing step. This scheme was developed for a model running in the spatial domain (cell by cell), and therefore not directly applicable in LPJmL, which is operated in discrete time step mode.

The second algorithm can be run within a routing model time step by time step (Hanasaki et al., 2006). However, this algorithm only accounts for two different purposes (irrigation and 'others') and is not integrated with an irrigation scheme. This means it does not simulate water extractions from the reservoir, but only addresses the redistribution of river water in time. In a more recent application of this scheme, water extractions are accounted for, but only from the local river and not directly from the reservoir (Hanasaki et al., 2008a; Hanasaki et al., 2008b).

To overcome the limitations of these two model approaches, a new reservoir scheme within LPJmL is developed by combining parts of both schemes and adding new functionalities.

A reservoir is considered in the model from the (simulation) year that it was built. This makes the model suitable to study the impacts of dams over time. The reservoir is filled daily with discharge from upstream and precipitation. Subsequently, the start of an operational year for a reservoir is defined similar to Hanasaki *et al.* (2006) and Haddeland *et al.* (2006b) as the month when mean monthly inflow shifts from being higher than the mean annual inflow to being lower than the mean annual inflow. If there is a reservoir upstream, this can influence the start month of the operational year for the downstream reservoirs. This definition is slightly different from Hanasaki *et al.* [2006] and Haddeland *et al.* [2006] who defined the start of the operational year based on natural flow simulations. At the beginning of the operational year, the actual storage in the reservoir is compared with the maximum storage capacity of the reservoir. To adjust the reservoir release to interannual fluctuations in inflow, a release coefficient is calculated as:

$$k_{rls,y} = S_{first,y} / \alpha C \tag{1}$$

where $S_{first,y}$ is the actual reservoir storage at the beginning of the operational year y, C is the maximum storage capacity of the reservoir and α is a dimensionless constant that can be interpreted as the preferred storage level at the start of the new operational year. For the study presented in this paper, α is set to 0.85, following Hanasaki et al. (2006).

A monthly 'target release' $r'_{m,y}$ (L d^{-1}) for month m in operational year y can be interpreted as the optimal release of the reservoir if reservoir capacity would not be limited. The target release depends on the function of the reservoir as in Hanasaki et al. (2006): for a reservoir that is not built primarily for irrigation (but e.g. hydropower, flood control, navigation), the target release is assumed to be constant

$$r'_{m,y} = i_{mean} \tag{2}$$

where i_{mean} is the mean annual inflow (L d^{-1}) over the last 20 years. The target release for irrigation reservoirs is defined as:

$$r'_{m,y} = \frac{i_{mean,m}}{10} + \frac{9}{10} \cdot i_{mean} \cdot \frac{d_{mean,m}}{d_{mean}} \qquad \text{if } d_{mean} \geq 0.5 \cdot i_{mean}$$

$$r'_{m,y} = i_{mean} + d_{mean,m} - d_{mean}, \qquad \text{if } d_{mean} < 0.5 \cdot i_{mean} \tag{3}$$

where $i_{mean,m}$ is the mean monthly inflow, and d_{mean} and $d_{mean,m}$ are the mean annual and mean monthly irrigation demand to the reservoir respectively (all in L d^{-1} calculated over the last 20 years). This release algorithm is based on Hanasaki et al. (2006), but has been slightly adjusted here so as to account only for irrigation water use while neglecting domestic and industrial extractions. Further, in Hanasaki's [2006] scheme the minimum release was set to 50% of the mean inflow (environmental flow requirement). In rivers with a strong seasonality, this means that the outflow in low flow months is much higher than in the natural situation, leaving no water available for irrigation. Therefore in the LPJmL scheme the minimum release is set to 10% of the mean monthly inflow, allowing the outflow to follow the irrigation demand as much as possible, but always leaving 10% of the mean monthly inflow in the river, following the natural intra-annual flow variability.

The actual reservoir release $r_{m,y}$ in month m year y (L d^{-1}) depends on the relative size of the reservoir as in Hanasaki et al. (2006):

$$r_{m,y} = \begin{cases} k_{rls,y} \times r'_{m,y}, (c \geq 0.5) \\ \left(\frac{c}{0.5}\right)^2 k_{rls,y} \times r'_{m,y} + \left\{1 - \left(\frac{c}{0.5}\right)^2\right\} i_{m,y}, (0 \leq c \leq 0.5) \end{cases} \quad (4)$$

where c equals maximum storage capacity / mean annual inflow

If the reservoir is not built for irrigation purposes, the water is released directly into the river. Otherwise, part of the released water can be diverted to irrigated land, except for the water needed to fulfil the environmental flow requirements. The area that can be supplied from a reservoir is estimated according to slightly modified rules of Haddeland et al. (2006b). All cells requesting water from a reservoir must lie at lower altitudes than the cell with the reservoir.

Further, they must either be situated along the main river downstream of the reservoir, or within reach of this main river at a distance of maximum 5 cells upstream (approx 250 km at the equator). Consequently, an irrigated cell can be supplied by two or more reservoirs, in which case the irrigation demand of that cell is shared between the reservoirs proportional to their mean volumes. The mean volume of water stored in a reservoir can change from year to year, and hence shares are updated annually.

Irrigation demands vary from day to day and water that is released for irrigation is made available for a 5 day period. If the water is not used within these 5 days, it is released back into the river, and hence storage possibilities in the conveyance system are simulated. A reservoir's total water demand is compared with the water that was released from the reservoirs for irrigation. If the total demand can only partly be fulfilled, all cells get the same percentage of the water they requested.

A summary of the operational rules for water supply from reservoirs can be found in figure 3.1.

3.2.3 Model setup and simulation protocol

LPJmL was run for the period 1901-2000, after a 990 year spin-up period (forced by repeating 1901-1930 climate and without irrigation and reservoirs), needed to bring carbon and water pools into equilibrium. The model was forced with monthly gridded values for temperature, precipitation, number of wet days and cloud cover from the CRU TS 2.1 climate data set (Mitchell and Jones, 2005). To get daily input forcings, those data were temporally downscaled: temperature and cloud cover were linearly interpolated, and daily precipitation values were obtained by applying a stochastic distribution method using the number of wet days (see Sitch et al., 2003).

The land use input consists of annual fractions of irrigated and non-irrigated crop types within each grid cell for the 20th century. This global crop and irrigation input dataset was developed by combining recently compiled datasets on rainfed and irrigated agriculture (Portmann et al., 2010), current crop distributions (Monfreda et al., 2008; Ramankutty et al., 2008b), and

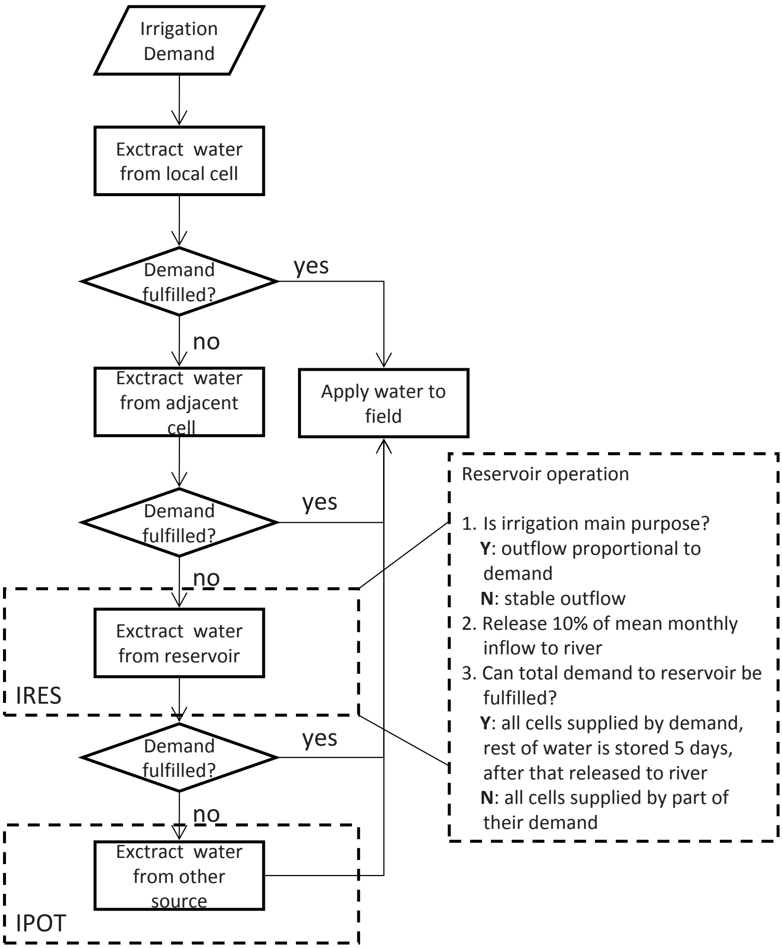


Figure 3.1. Schematic representation of the reservoir and irrigation algortithm in LPJmL. Water from reservoirs can only be extracted in a simulation which includes reservoir operations (IRES). The right box contains a summary of the rules for reservoir operation. Water from other sources can only be applied in a simulation that assumes unlimited supply (IPOT).

historical land use information (Klein Goldewijk and van Drecht, 2006) (for details see Fader et al., 2010).

Information on natural lakes is obtained from the global lake and wetland database (GLWD) (Lehner and Döll, 2004). The locations of the reservoirs are obtained from the recently released GRanD database (Lehner et al., 2011). This global database contains geographical locations for approximately 7,000 dams, including information on construction year, maximum storage capacity, surface area and functions (see Figures 3.2 and 3.3).

The representation of the river system is simplified to a 0.5˚ grid network (Vörösmarty et al., 2000b). Therefore, not all reservoirs (which have exact geographical locations) are placed on the right tributary in the modelled river system. The locations of all (190) reservoirs with a capacity greater than 5 km³ have been checked and if necessary relocated on the network. Observed discharge data, to compare with simulated discharge values, were obtained from the Global Runoff Data Centre (GRDC, 2007).

In this study four simulations are performed:

(1) A model run without irrigation and reservoirs (as in Biemans et al., 2009, chapter 2), simulating discharge without human extractions and river flow alterations. (INO)

(2) A model run with irrigation extractions, assuming that there are no managed reservoirs and irrigation is limited to the local surface water available in natural lakes and rivers (ILIM; see also Rost *et al.* [2008])

(3) A model run with irrigation extractions and reservoir operation, assuming that this irrigation is limited to the local surface water available in lakes, rivers and reservoirs (IRES)

(4) A model run with irrigation extractions, without reservoir operations, assuming that irrigation water can always be supplied, regardless of the source of the irrigation water (IPOT).

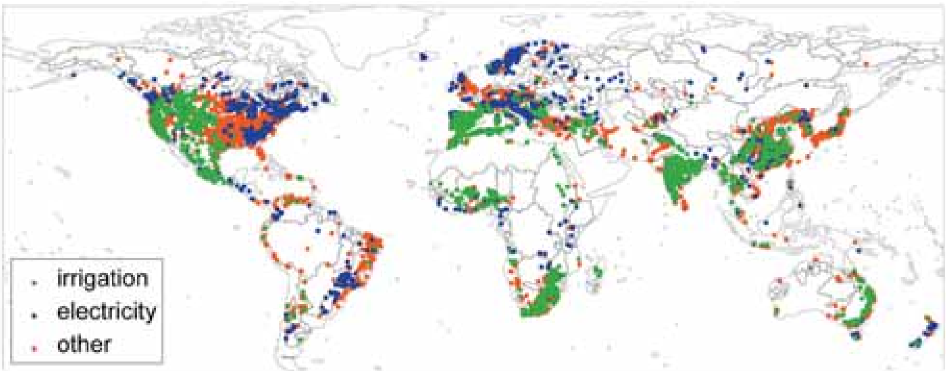


Figure 3.2. Reservoirs included in the GRanD database and their main function. If reservoirs have multiple functions the most important function is shown. Included are all reservoirs built before 2008.

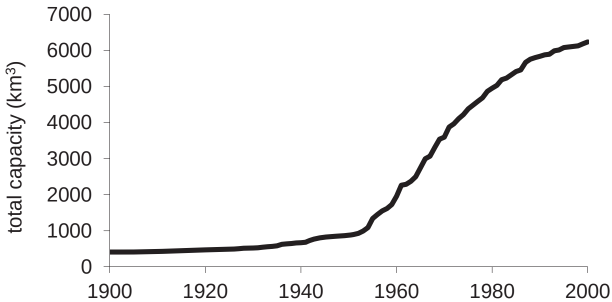


Figure 3.3. Cumulative storage capacity of large reservoirs during the 20th century, derived from the GRanD database.

3.2.4 Analyses

For model validation purposes, discharges simulated by the runs INO and IRES are compared. The difference between those two runs shows the combined impact of reservoir operations and irrigation withdrawals on discharge in these basins. To evaluate whether the reservoir model improves the discharge simulations, mean monthly discharge results and discharge time series for seven large affected basins are presented and compared with observations. The model is further validated by comparing simulated discharge with observations at 522 gauging stations (as in Biemans et al. (2009), chapter 2 and Fekete et al. (2002)) both for INO and IRES simulations. The quality of the simulation is estimated by calculating the root mean square error, normalized by the mean of the observations as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(o_i - s_i)^2}{n}}\,\frac{1}{\bar{o}} \tag{5}$$

where n is the amount of observations, o_i is the observed discharge and s_i the simulated discharge at time step i, ō is the mean of all observations.

After the validation, the model was applied to calculate the impact of irrigation extractions and reservoir operations on mean monthly global and continental discharge.

Another measure to quantify the hydrological effect of flow regulations on rivers spatially is the amended annual proportional flow deviation (AAPFD) indicator (Ladson and White, 1999; Marchant and Hehir, 2002) .The AAPFD expresses changes in monthly flow as a proportion of the natural flow for each month:

$$AAPFD = \frac{1}{nyears}\sum_{j=1}^{nyears}\left(\sum_{i=1}^{12}\left(\frac{(c_{ij} - n_{ij}}{\overline{n}_j}\right)^2\right)^{\frac{1}{2}} \tag{6}$$

where c_{ij} is the actual discharge in month i year j, n_{ij} is the natural discharge in month i year j, and $\overline{n}_j$ is the mean natural discharge in year j. The AAPFD indicates the level of modification of a river system and can be calculated at every arbitrary point in the river basin if both modified and natural discharge data are available. The AAPFD is calculated in every grid cell, based on the INO and IRES simulations. It gives a good spatial overview of the river stretches most affected by reservoirs and irrigation extractions.

Subsequently this study evaluates the contribution of reservoirs to irrigation water supply during the 20th century, by comparing simulated irrigation extractions of the runs ILIM, IRES and IPOT. The ILIM run estimates the water that is available for irrigation in the natural system of lakes and rivers. The IRES simulation estimates availability including the water in managed reservoirs. The IPOT simulation estimates extractions under unlimited supply and can be interpreted as the total water demand for irrigation.

Total global water extractions for irrigation as simulated by ILIM, IRES and IPOT during the 20th century were compared to estimate the contribution of reservoirs to irrigation supply. Because the reservoir model uses only one set of rules to simulate reservoir operations globally, the sensitivity of the estimated water supply from reservoirs for the chosen model parameters ws tested. One by one, three main parameters have been varied : the size of the area that can be supplied by the reservoir, the time water can be stored in the conveyance system, and the environmental flow requirement. For comparison, the influence for reservoir capacity was also tested.

Finally the contributions of reservoirs to irrigation were calculated for continents and basins. For some specific basins, the effect of reservoirs on intra-annual water supply was analysed.

3.3 Results

3.3.1 Discharge validation

Figure 3.4 shows a comparison of simulated discharge with observations at seven locations that are known to be influenced by reservoir operations and irrigation extractions. The construction of the Glen Canyon reservoir (1963) just upstream of the Lees Ferry stream gauging station in the Colorado River basin is clearly visible in both the observed and simulated time series. In other basins the effect of the introduction of a large reservoir is less obvious, because the stream gauge is not located directly downstream of the reservoir or streamflow is less affected by reservoirs. The mean monthly figures show that the reservoir module changes the discharge timing significantly. In all example basins both the timing and the total of the IRES simulation is closer to the observed discharge than the INO simulation.

For a broader analysis of the performance of the model at global scale, the root mean square error (RMSE, normalized to the mean of the observations) was calculated for 522 GRDC stations, both for the INO as for the IRES run. For 304 stations there was a difference in RMSE between the two simulations, because the basin was impacted by reservoirs and irrigation (the grey shades in figure 3.5 show the storage capacity to mean annual runoff ratio). At 279 locations the RMSE improved when including the impact of reservoirs and irrigation in the simulation, at 104 stations this improvement was more than 0.25 and for 37 cases even more than 1 (figure 3.5). In some basins in south and south-east Asia, the red dots suggest that including the calculation reservoir operations has decreased model performance in those basins.

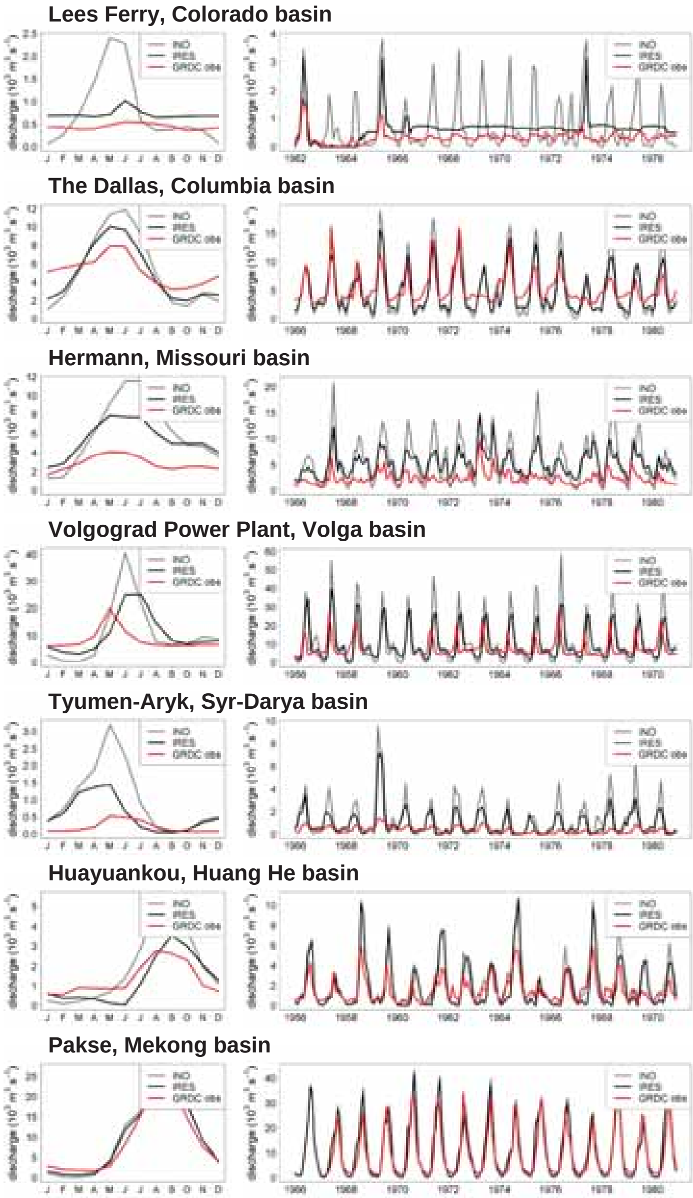


Figure 3.4. Mean monthly (left) and time series (right) of stream flow simulations for test basins. Note that not all time series are plotted for the same period. Presentation of results focussed on periods when complete data sets were available or when a big dam was built upstream of the station (as for example in 1963 the Glen Canyon Dam just upstream of Lees Ferry station), or a period that has complete data availability. The mean monthly discharge calculations are based on the period 1981-2000 for all stations, but only include the years for which data was available in this period.

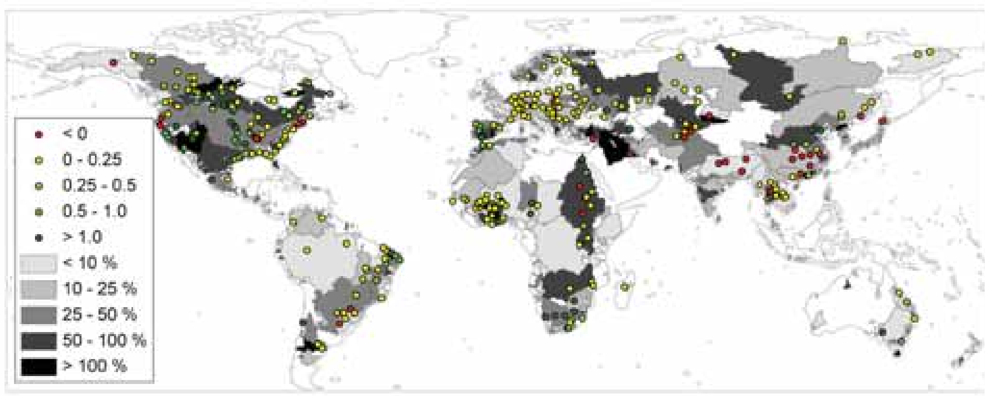


Figure 3.5. Grey shades: total reservoir storage in the basin (2000 from GranD data) compared to the mean annual runoff (1981-2000, LPJmL simulations) in %. Circles: Absolute difference between the normalized root mean square errors (RMSE) of the INO and IRES run (1981-2000). Yellow to green dots reflect an improvement of the NRMSE when reservoir operation and irrigation extractions are included in the simulations. Only results for affected basins are shown.

3.3.2 Effects of reservoirs and irrigation on discharge

Figure 3.6 shows that the global annual discharge into oceans and large inland water bodies is reduced by human activities. Simulation results indicate that without reservoirs the irrigation extractions only (ILIM) decrease the total global discharge by about 1 to 2 % per month, with the strongest relative effect in the period from May to August (figure 3.6). The total mean annual decrease in discharge (1981-2000) is 1.2% or 540 km^3 (but note that additional supply from other sources than surface water is not taken into account as was done in the study of Gerten *et al.* (2008)). The effect of irrigation extractions and reservoir management together (IRES), however, shows a more profound pattern. From May to August, global discharge is lowered up to 5%, due to increased irrigation water withdrawals from reservoirs. This is partly offset by an increase in the October to March discharge of up to 2% caused by the extra releases from non-irrigation reservoirs during low flow months. The cumulative effect of reservoir management and irrigation extractions leads to a mean annual decrease in global discharge of 2.1% or 930 km^3.

The largest effect of extractions for irrigation only (ILIM) on discharge fluxes can be seen in the summer in Europe (June to September) and North America (July, August) and in spring in Asia (March, April, May) (figure 3.6). When reservoir operations are included in the simulations (IRES), the effect on discharge is much larger in all continents. Simulation results indicate that there is cumulative effect of reservoir operations and irrigation extractions on discharge in all continents. The strongest effects are again seen in the continents with large irrigated areas and many human built reservoirs (Europe, Africa, Asia and North America), where increases up to

5% and decreases up to 10% are estimated in different months of the year (figure 3.6). At the annual timescale, the decrease in discharge is largest in North America (on average 2% or 138 km^3 lower than in the natural situation) and Asia (4.0%, 607 km^3).

Comparing of the Amended Annual Proportional Flow Deviation (AAPFD) for the first two (1901-1920) and the last two decades (1981-2000) of the 20th century, clearly shows that the river systems are much more modified in the late 20th century than in the early 20th century (figure 3.7). During the course of the century reservoirs have been built in Scandinavia, Northern Russia, the Nile basin, and North America, and the effect on discharge are obvious. Further, it can be seen that in the heavily irrigated areas in India, South-East Asia and the United States the reservoir operations also influence the river branches. This is mainly caused by the effect irrigation has on redistributing the water, which increases the discharge in dry areas, because of inefficient irrigation (return flows). The reservoirs not built for irrigation purposes have a strong impact on the discharge, but the effect is restricted to the main river (figure 3.7). It can also be seen that the effect is greatest close to the dams and dampens out further downstream (see for example in the northern Russian river basins).

3.3.3 Effects of reservoirs on water availability for agriculture

During the 20th century, a rapid increase in the number of large reservoirs, has significantly increased the available water resources for irrigation (figure 3.8). LPJmL simulations indicate that between 1981-2000, average irrigation water demand was 2650 km^3 $year^{-1}$. If there would not have been artificial reservoirs, 1250 km^3 $year^{-1}$ of this demand could be extracted from surface water. Another 460 km^3 $year^{-1}$ (which is an extra 37%) has been made available from managed reservoirs. The remaining 940 km^3 $year^{-1}$ might have been supplied from other sources (eg. groundwater) or has partly not be supplied because of water shortages. At the beginning of the 20th century (1901-1920), reservoirs supplied only 19 km^3 $year^{-1}$ (5% extra).

Results of the parameter sensitivity analysis (table 3.1) show that this estimated mean annual reservoir withdrawal of 460 km^3 (for 1981-2000) would be 17 km^3 $year^{-1}$ higher under the assumption that the reservoirs could distribute their water 8 cells upstream of the main river (but still lower than the reservoir in altitude) instead of 5. Similarly, restricting the area to 2 cells upstream of the main river would decrease the estimated annual withdrawal with 80 km^3. Application of a larger environmental flow requirement of 20% decreased the estimated reservoir withdrawals with 16 km^3 $year^{-1}$, versus an increase of 13 km^3 $year^{-1}$ when the total reservoir outflow could be used for irrigation. The effect of assuming a longer (8 days) or shorter period (2 days) of conveyance storage is only 5 km^3 $year^{-1}$ or -7 km^3 $year^{-1}$ respectively. The factor most influencing the estimate of reservoir supply is the reservoir capacity; doubling or halving all reservoirs' capacities, changes the total annual supply by +92 km^3 or -99 km^3 respectively.

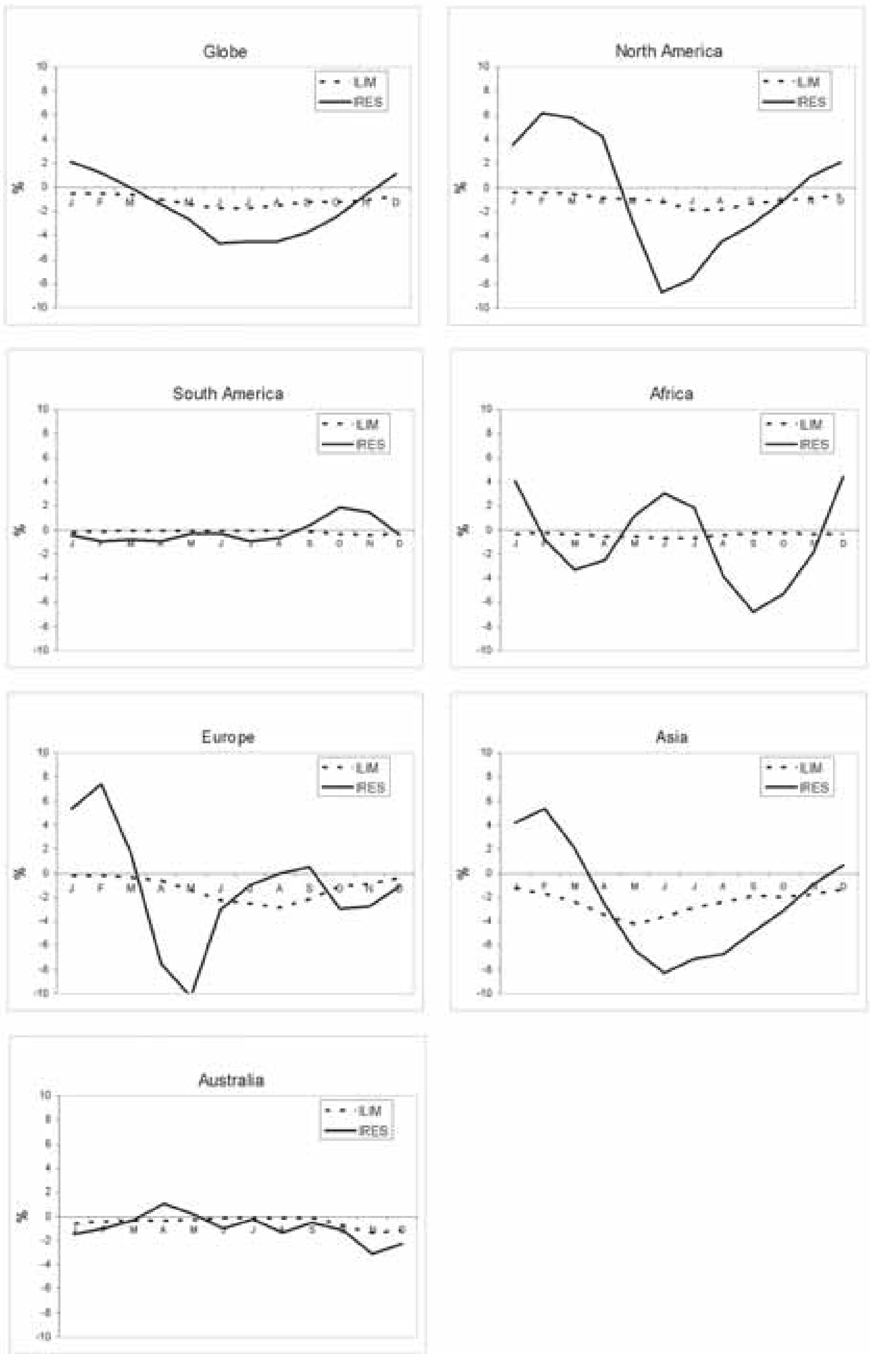


Figure 3.6. Relative difference in mean monthly discharge at river mouths (in % compared to the 'natural' situation simulated by INO) for the period 1981-2000. Dashed line shows the effect of irrigation extractions alone, solid line shows the cumulative effect of reservoir operations and irrigation extractions.

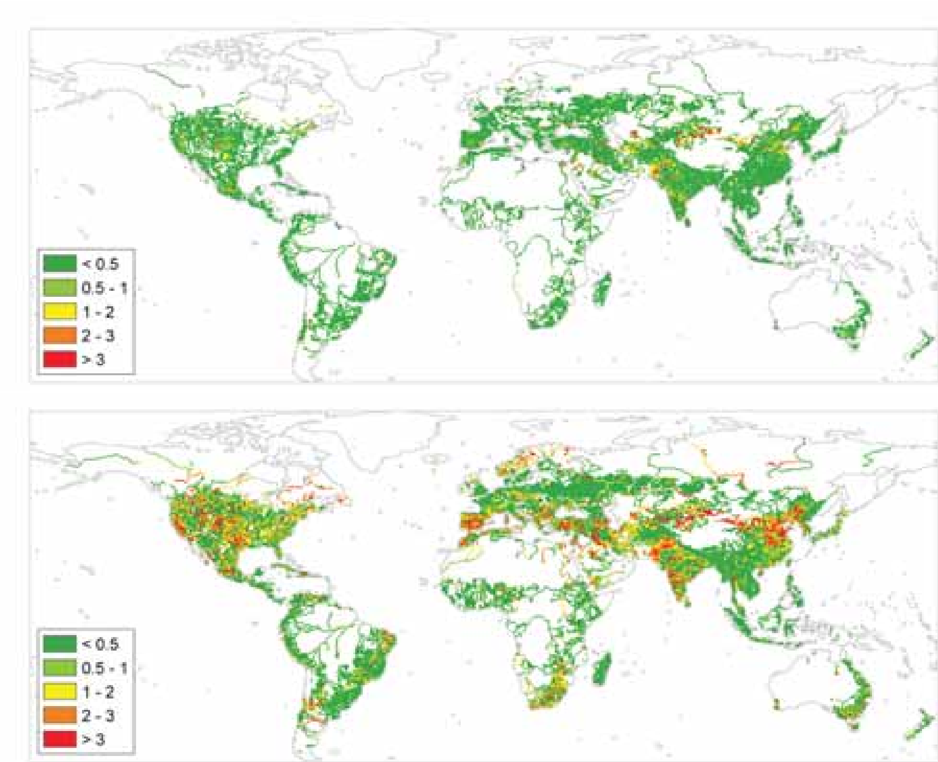


Figure 3.7. Average Amended Annual Proportional Flow Deviation (AAPFD) for 1901-1920 (upper) and 1981-2000 (lower).

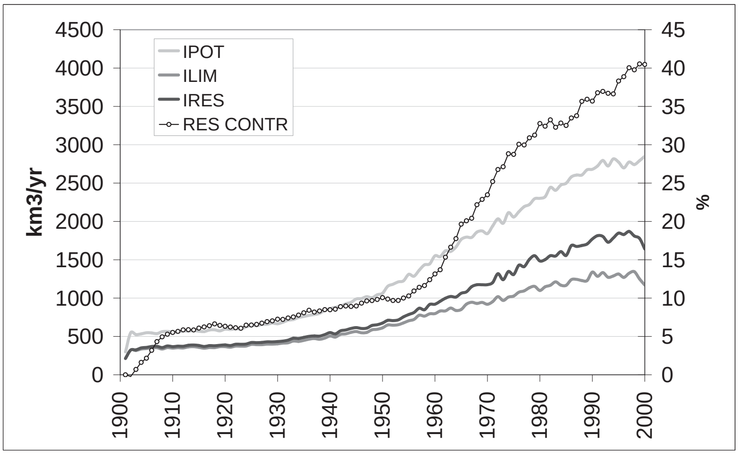


Figure 3.8. 20th century development in the annual global irrigation withdrawal as simulated by LPJmL for ILIM, IRES and IPOT. IPOT can be interpreted as the total irrigation water demand. The circles (right axis) show the additional supply contributed by reservoirs (averaged over last years), compared to a simulation without reservoirs.

Asia is by far the largest water user of irrigation water in terms of volume (figure 3.9). During the second half of the 20th century, Asia has built many reservoirs and almost tripled its surface water withdrawals for irrigation. Partly, this additional water is supplied from new reservoirs: the contribution of reservoirs to irrigation water supply increased from around 40 km^3 $year^{-1}$ (8%) in1941-1960 to 360 km^3 $year^{-1}$ (38%) in 1981-2000 (figure 3.9). In North America, most reservoirs are older. The contribution of reservoirs was already large in the fifties and has increased from 19 km^3 $year^{-1}$ (25%) to 57 km^3 $year^{-1}$ (38%) during the same period. In relative terms, Africa, North America and Asia gain the most from their reservoirs which increased the water supply with around 40 %.

The contribution of reservoirs to irrigation water supply differs considerably more per basin (figure 3.10). Basins that experienced the largest increase in supply by reservoirs are in the US (Colorado, Columbia), several basins in India and Central Asia, and some large basins in East Asia and Africa. In Europe, basins in Spain gain the most water from their irrigation reservoirs. Figure 3.11 focuses on a few basins that supply a large part of their irrigation water from reservoirs. In the Colorado and Columbia River basins, reservoirs have significantly increased irrigation water supply compared to a situation without reservoirs. It both these basins, with additional supply from reservoirs, the irrigation demand (derived from from IPOT simulation) can almost be met by surface water extractions only.

In the Asian basins, the picture is different. In these basins, there is large intra-annual variability in water supply due to a distinct dry and wet season. Reservoirs (partly) mitigate these seasonal

Table 3.1. Sensitivity analysis on model parameters in the reservoir operation model: irrigation water withdrawals.

Simulation	Mean annual total irrigation withdrawal from reservoirs ($km^3 year^{-1}$) (1981-2000)	difference wrt IRES ($km^3 year^{-1}$)
IRES	460	-
Area +[a]	477	+17 (3.6%)
Area -[a]	380	- 80 (-17.4%)
Days +[b]	465	+5 (1.1%)
Days -[b]	453	-7 (-1.5%)
Env flow +[c]	444	-16 (-3.5%)
Env flow -[c]	473	+13 (2.8%)
Capacity +[d]	552	+92 (20.0%)
Capacity -[d]	361	- 99 (-21.5%)

[a] The amount of cells that can get water from the reservoir is increased to 8 cells or decreased to 2 cells upstream of the river below the reservoir (compared to 5 cells in IRES).

[b] The time that released water from the reservoir is stored in the conveyance system is increased to 8 days or decreased to 2 days (compared to 5 days in IRES)

[c] The minimum flow that is required in the river is decreased to 0% or increased to 20% of the mean monthly inflow (compared to 10% in IRES).

[d] The capacaties of all reservoirs are doubled or divided by 2.

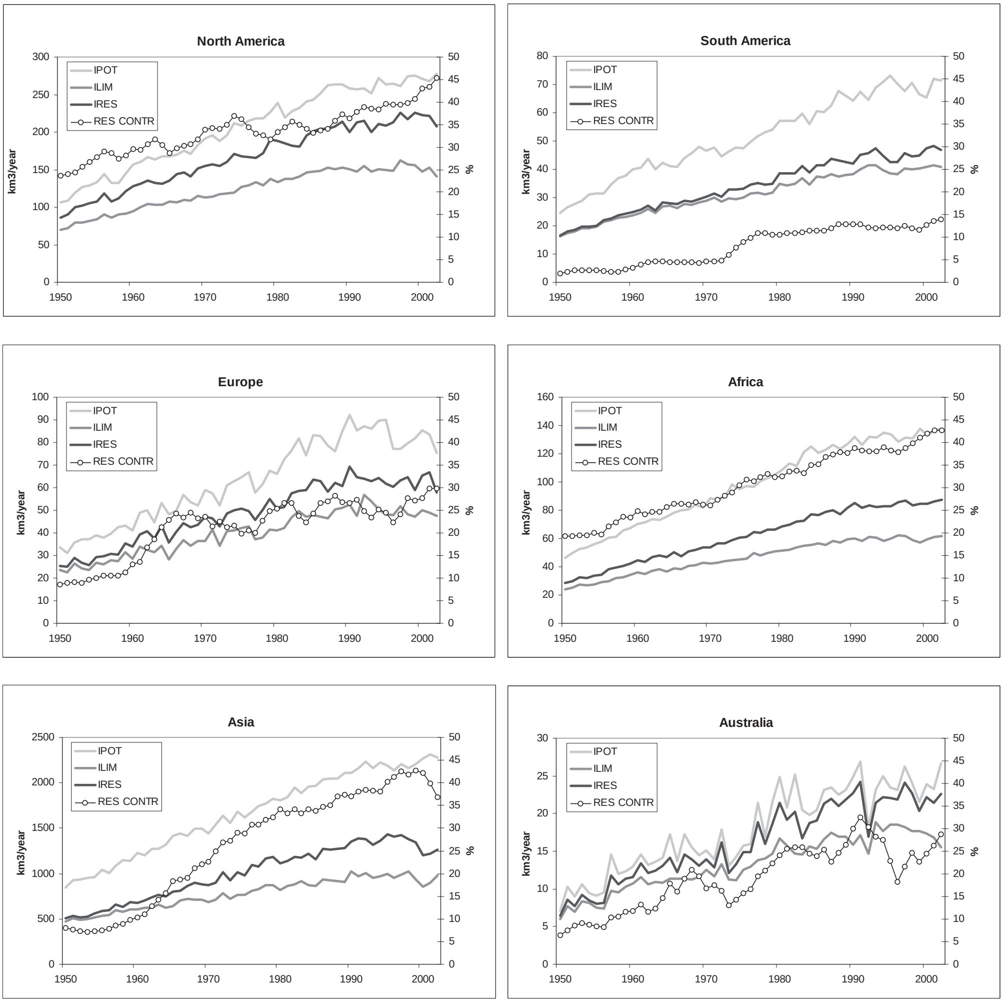


Figure 3.9. Same as figure 3.7, but for different continents: 1950-2000 development in the total continental annual irrigation withdrawals as simulated by LPJmL, as well as the additional supply contributed by reservoirs compared to a simulation without reservoir (right axis).

difference in water availability. As a result, with reservoirs more water becomes available for irrigation. This is especially the case in the Krishna basin (figure 3.11).

3.4 Discussion

This study demonstrated that introducing a reservoir operation and irrigation module in the LPJmL global hydrology and vegetation model significantly improves the simulation of discharge in basins where human impacts on the 'natural' hydrology are known to be large. A validation was performed by showing simulated time series and mean monthly discharge

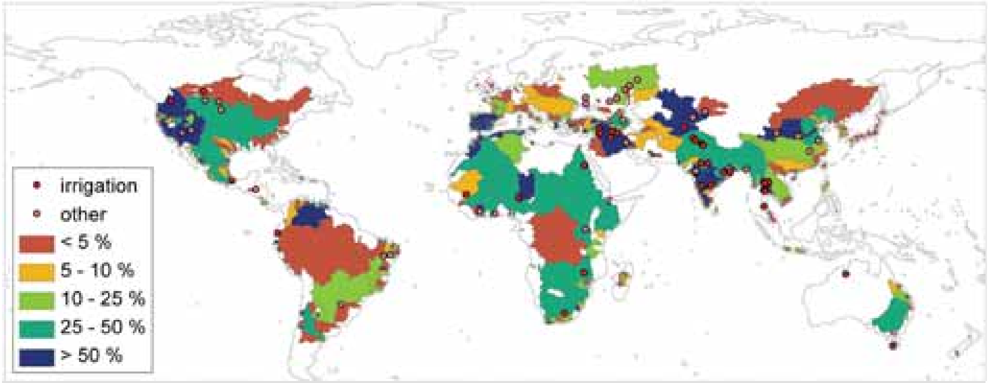


Figure 3.10. LPJmL simulated contributions of reservoirs to total irrigation water supply (average over 1981-2000). Colors represent the percentage of extra water that was irrigated in the reservoir simulation compared to a simulation without reservoirs (IRES vs ILIM) for the period 1981-2000. The dots represent all reservoirs larger than 5 km3 from which irrigation water is supplied: in red the irrigation reservoirs, in pink the reservoirs that are primarily built for other purposes, but do supply irrigation water.

values of affected rivers. Further, an analysis of simulated discharge at 304 gauging station locations with reservoirs upstream showed an improvement of the RMSE in 91% of the cases. The reservoir model used in this study generalizes the operation of large reservoirs at global scale, and does not include local information on the management of individual reservoirs. A sensitivity analysis showed that the reservoir model is more sensitive to total reservoir capacity, than to chosen model parameters. This result increases the confidence in the estimate of global irrigation supply from reservoirs. However, there might be stronger sensitivities in particular basins.

Since the model is flexible and rules can be changed, the model can easily be adjusted to include specific local information on management or irrigation practices in large river basins, and could therefore be made more suitable for river basin studies. Further, the model can now be used to study the combined impacts of climate change and reservoir scenarios both on discharge and regional water supply.

There are several other uncertainties regarding model input and model algorithms that could have influenced the results. As discussed in chapter 2 (Biemans et al. (2009)) part of over- or underestimations in simulated streamflow (see figure 3.4) are inevitable and might be attributed to the forcing data. From figure 3.5 one can conclude that adding the reservoir module does not improve the simulation of discharge in some basins, mainly in India and China. This might have different reasons. India and China are amongst the countries with the highest irrigation water demands. Simulated outflow of irrigation reservoirs is to a large extent depending on simulated growing season, because it is following irrigation water demands. Therefore, the right representation of sowing dates is essential. A new sowing date algorithm is currently being developed and could possibly improve the timing of the growing season.

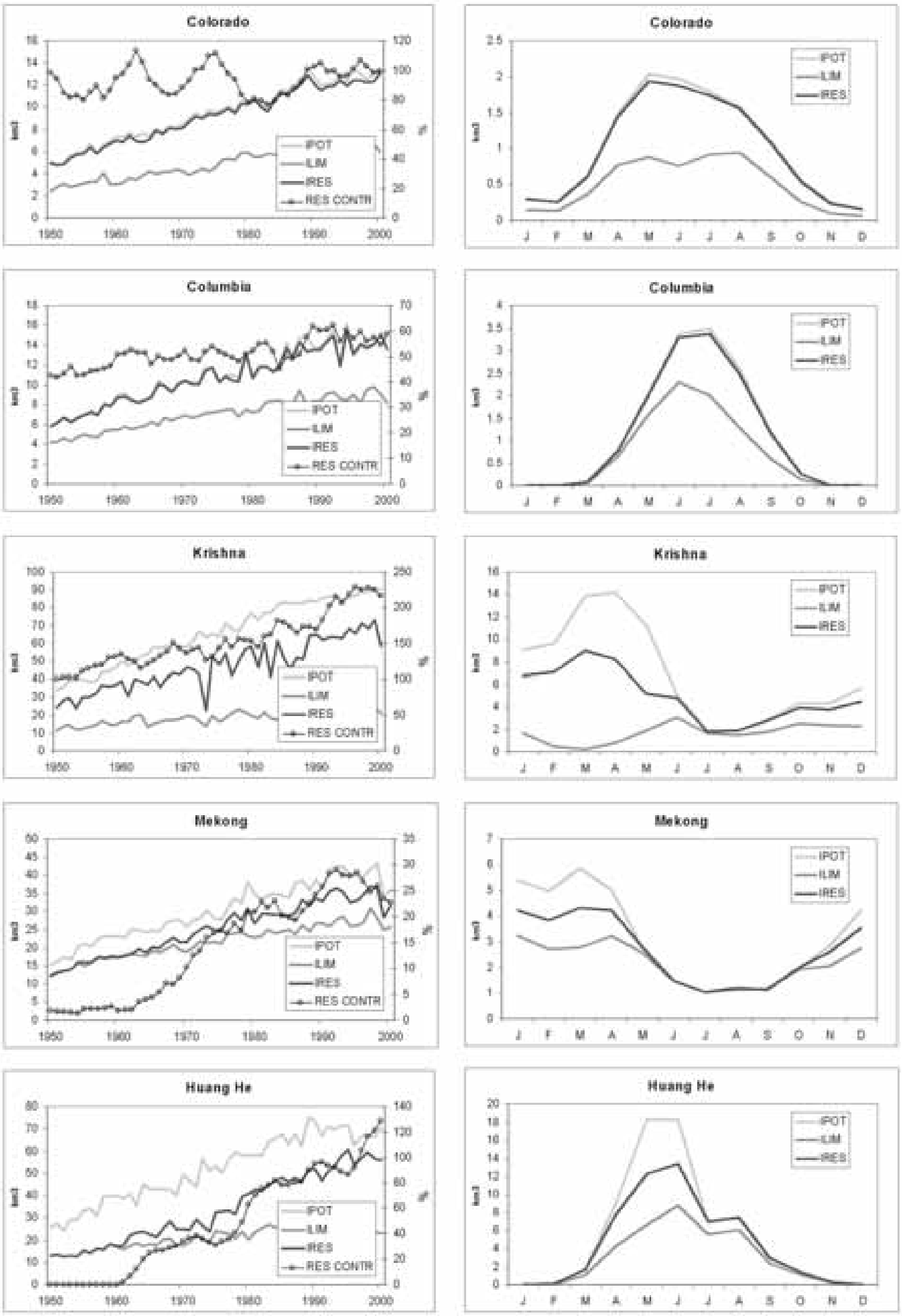


Figure 3.11. left: 1950-2000 development in the total annual irrigation withdrawal water as simulated by LPJmL, right: mean monthly irrigation withdrawal in 1981-2000. IPOT line represents the withdrawal if water would not be limited, ILIM line represents the water withdrawal from rivers and natural lakes only and the IRES line represents the supply from rivers, natural lakes and operated reservoirs. Dotted line is the percentage additional water supplied in the simulation with reservoirs compared to a simulation without reservoirs.

Further, although rice is allowed to grow twice a year in tropical Asia, there is no simulation of the multiple cropping systems like the rice-wheat systems in South Asia, or the wheat-soybean or maize-soybean systems in North America (Bondeau et al., 2007). Ignoring multiple cropping might underestimate irrigation water demand in those areas.

Globally, groundwater withdrawals are estimated at 600-700 km^3 year^{-1} (Foster and Chilton, 2003) and in many countries groundwater forms an important contribution to irrigation water supply. Although there is no explicit representation of (fossil) groundwater in the model, the difference between surface water irrigation (IRES) and unlimited irrigation (IPOT) could partly be attributed to groundwater extraction. However, with the current model, it is not possible to evaluate actual groundwater availability and its limits. First attempts to include groundwater in global scale hydrological models are currently being made (Döll and Fiedler, 2008).

The most complete global list of large dams is provided by ICOLD (2007). However, this list does not contain information on geographical locations, and is therefore not suitable to be used in hydrological models. The cumulative capacity estimated by Chao et al. (2008), based on ICOLD) is 8,300 km^3, whereas the GRanD database used in this study includes 6,300 km^3 of storage. This means that the contribution of large reservoirs to irrigation water supply might be even higher than the here reported 460 km^3 year^{-1}.

The total area used for irrigation in 2000 in the here used land use dataset (Fader et al., 2010) is estimated at 215 Mha. This estimate is derived from the global map of areas equipped for irrigation (GMIA) (Siebert et al., 2005), but is significantly lower than their 270 Mha. This is because the areas that are not actually in use for irrigation (e.g. because of damaged infrastructure or water shortage) were excluded. Wisser *et al.* (2008) showed that estimates of global irrigation demand are very sensitive to the selected dataset for irrigated area and climate. This means that using another land use dataset, e.g. another map of areas suited for irrigation (e.g. Thenkabail et al., 2008), could lead to a much higher or lower estimation of irrigation water demand, and consequently to a different impact of reservoirs.

3.5 Conclusions

In this study, a global scale model was developed which is able to simulate the impact of large reservoirs on the global water cycle. This model was tested and applied to quantify the impact of reservoirs on discharge and irrigation water supply in the 20th century.

At continental and global scale, irrigation extractions and reservoir operation affect both the timing and the total amount of discharge reaching the oceans. Impacts of large reservoirs are most profound in Asia, Europe, and Africa, where in some months the total flux of freshwater into the ocean is 10% less compared to a naturalized situation. Averaged over the year, irrigation (including irrigation from reservoirs) decreases global discharge with 2.1%, or approximately 930 km^3.

It was also showed that the global surface water extractions for irrigation have significantly increased through the construction of large reservoirs during the 20th century. At the beginning of the century reservoirs added around 5% to irrigation supply from surface water; at the end this was 40%. In absolute terms, the global annual average irrigation extractions from reservoirs increased from 18 km^3 $year^{-1}$ in the beginning (1901-1920) to 460 km^3 $year^{-1}$ at the end of the century (1981-2000). This increase occurred mostly in continents with large irrigated areas and many irrigation dams.

A more detailed analyses at river basin scale confirmed that the irrigation reservoirs are able to make more water available in specific seasons, especially in some Asian basins such as the Krishna and Huang He (around 200% and 130% more, respectively), where natural water availability is highly variable throughout the year. The reservoirs retain the water to be released during a water scarce period.

The analysis performed in this study showed the importance of reservoirs for sustaining irrigated agriculture. By storing and redistributing water, reservoirs significantly increase water availability for irrigation. As an effect of climate change and socio economic change, however, irrigation and other water demands are expected to grow and put more pressure on available water resources (e.g. Alcamo et al., 2007; Döll, 2002). In some regions, the current reservoir system might not be able to fulfil an increase in demand, or might not be able to continue the same supply because of a change in reservoir inflow. On the other hand, reservoirs might have an increasing role in meeting future water requirements in regions where water stress is an issue of distribution rather than an absolute shortage.

The ability of the here developed model to quantify the effect of large reservoirs on the 20th century irrigation water supply, makes it also a very useful tool to estimate the impact of global change scenarios, *e.g.* to assess the changing role of reservoirs in sustaining water supply for irrigation.

Acknowledgements

This research was supported by the Strategic Research Programme Climate Change (KB2, 2008-2010) of the then Dutch Ministry of Agriculture, Nature and Food Quality, by the European Union (FP6) funded projects WATCH (Grant nr. 36946) and SCENES (Grant nr. 36822), and by the Netherlands Environmental Assessment Agency (PBL). Thanks to Bernhard Lehner for the provision of the GRanD data, and to the GRDC for the streamflow observation data. The authors would also like to thank three anonymous reviewers for their very useful comments.

4

Water constraints on future food production

To feed a growing and wealthier global population, total food and feed production needs to more than double in this century. Here we show that in many river basins production increases as projected in agricultural scenarios will not be possible in many river basins due to limited water availability. We quantify that roughly 25% [~1200 km^3] of the irrigation water demand by the end of the century cannot be met, causing a reduction of annual irrigated crop production of about 20% (i.e. ~400 Mton dry matter). This water shortage can almost entirely be associated with higher water demands due to agricultural land expansion and intensification. Climate change will increase scarcity in some regions but this is offset by reduced scarcity elsewhere. Regions where food production will be most at risk include basins in Southern Africa and South Asia, where production losses can be over 50%. Unless considerable efforts are made to improve water infrastructure and water use efficiency, water will put a serious constraint on future global food production.

Based on:

Biemans, H., P. Kabat , E. Stehfest, F. Ludwig, D. Gerten. Water constraints on future food production (in preparation)

During the 21st century, the world will become more populous and wealthier than today (Grubler et al., 2007; Nakicenovic and Swart, 2000). This will result in much higher food and feed demands. The required increase in agricultural production can be achieved by intensification or expansion of agricultural area (FAO, 2006; Godfray et al., 2010). Intensification is often seen as the preferred option because it has lower environmental impacts than crop land expansion (Foley et al., 2011; Tilman et al., 2011).

One of the options to intensify agriculture is irrigation, because irrigated crops generally attain higher yields than rainfed crops. Irrigation also reduces the vulnerability to crop losses due to by inter-annual variations in precipitation and temperature (Molden, 2007) and it allows for more crop cycles per year compared to rainfed areas.

Irrigation has always played an important role in global food production, but especially during the last 50 years, when the extent of global irrigated cropland doubled (Freydank and Siebert, 2008) (Foley et al., 2005). By the end of the 20th century, irrigated areas produced 33 percent of all global crops on only 17 percent of the agricultural area (Portmann et al., 2010; Siebert and Döll, 2010).

Several global agricultural scenarios project that an expansion of irrigated agriculture will be required to meet the world's growing food demand (FAO, 2006; FAO, 2011; Fischer et al., 2005; Molden, 2007). Comprehensive scenarios for future agricultural land use were created by combining a crop productivity model with a global economic model and assumptions on regional diet preferences, technology development and trade. Implicitly is assumed that water availability will not limit irrigated area expansion and that adequate water supply will always remain available. Several hydrological assessments however have shown that water scarcity will increasingly threaten future food supply (Falkenmark et al., 2009; Gerten et al., 2011), but they did not quantify the impact of this water scarcity on crop production.

This study presents an integrated analysis of future global water resources and agricultural production. Using the global hydrology and vegetation model LPJmL we analyze the combined effects of land use change, agricultural intensification and climate change on water resources availability and irrigation demand as well as crop production. We explicitly quantify if enough water is available to supply future irrigated areas and quantify the impact of limited water availability on the future food production.

Recent projections for future rainfed and irrigated cropland extent (Fischer et al., 2005; Fischer et al., 2007) were combined with current crop distributions (Fader et al., 2010) to create land use datasets representing IPCC-SRES B1 and A2 scenarios (Nakicenovic and Swart, 2000) for the year 2100. The B1 scenario reflects a world with limited climate change and a global population that first increases to 9 billion but after that declines towards 7 billion in 2100 (Grubler et al., 2007). Globalization and rapid economic growth results in relative high per capita food demand. The total agricultural area will increase with only 2%, but there is a major conversion from rainfed to irrigated agriculture resulting in an irrigated area expansion of 31% compared to 2000 (Figure 4.1a, table A1). In contrast, A2 projects more climate change, a population growth towards 12 billion in 2100 (Grubler et al., 2007), but a smaller per capita food demand. According to this scenario, the total agricultural area will increase with 19%, and the irrigated area with 44% (Figure 4.1a, table A1).

Agricultural intensification is represented by crop and country specific projections for yield growth from the same agricultural scenarios (Fischer et al., 2005; Fischer et al., 2007) (Table A2). Those projected growth rates were combined with observed yields from 1991-2000 (FAO, 2012a) to create yield projections for 2091-2100. In both B1 and A2 the global average yields are projected to more than double between the years 2000 and 2100 (107% and 113% increase respectively) (Figure 4.1b), but with profound differences between regions and crops (table A2).

Crop and country specific management factors in LPJmL were calibrated to reproduce the current and projected future yields for 12 important food and feed crop groups (table A3) (Bondeau et al., 2007; Fader et al., 2010). Similar to the agricultural scenarios, the effect of climate change was included, but without limitation in irrigation water supply.

The model was run with daily bias-corrected outputs of three global climate models (GCMs), both for current (1981-2000) and future climate (2081-2100) for the IPCC-SRES B1 and A2 emission scenarios (Hagemann et al., 2011) to simulate the effect of changes in climate on riverflow (Figure A2).

LPJmL calculates daily river flows and irrigation water demand based on crop water requirements and country specific irrigation efficiencies (Rost et al., 2008). If available, irrigation water can be supplied from different water sources: surface water including human build reservoirs (Biemans et al., 2011, chapter 3) and renewable or fossil groundwater (based on Siebert et al., 2010). By successively excluding certain water sources in a series of model runs, we estimate the contribution of different water sources to irrigation water supply. The hydrological cycle and carbon cycle are explicitly linked by the model's photosynthesis representation. Therefore effects of limited water availability on crop production could be quantified. To distinguish impacts of land use change and intensification from impacts of climate change, we ran a second set of simulations with changed land use and management factors, using the 1981-2000 climatic conditions (See Annex A for additional information on the materials and methods).

If all irrigation water is assumed to be available, our simulations show that agricultural expansion and intensification could result in an average annual food crop production of 4556-5490 Mt dry matter harvestable products for 2081-2100 (B1-A2). This is a 76-112% (B1-A2) increase compared to 1981-2000 (table 4.1), which is in line with the agricultural scenarios (Fischer et al., 2005; Tilman et al., 2011). Related to the higher crop production, irrigation water demand will increase by 30% (Table 4.1). For both the B1 and A2 scenarios higher

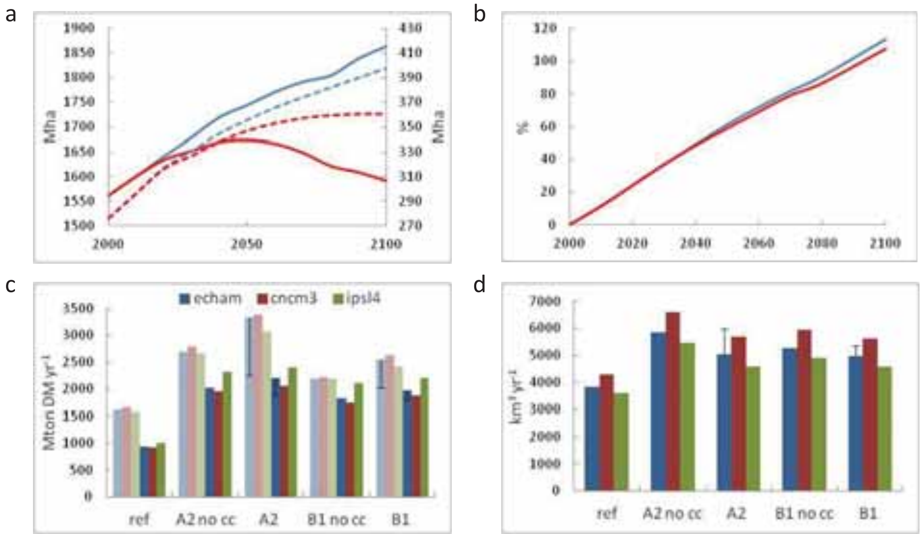


Figure 4.1 Global agricultural scenarios (**a**) projected changes in total global agricultural area in Mha (solid lines, left axis) and irrigated area (dotted lines, right axis) for B1 (blue) and A1 (red), (**b**) projected changes in global average crop yields with respect to 2000 for B1 (blue) and A2 (red). For region specific land use change and yield growth projections see table A1 and A2 (**c-d**) Total attainable rainfed (light colors) and irrigated (dark colors) food and feed crop production (c) and irrigation water demand (d) for current (1981-2000, ref) and future (2081-2100, B1 and A2) landuse and crop production, with and without accounting for the effect of climate change, all under te assumption that irrigation water is available. Error bars relate to the uncertainty related to the magnitude of the effect of CO_2 fertilization and show ECHAM result for a simulation with CO_2 concentration kept constant at the level of the year 2000.

production and increased irrigation water demand are mainly the result of land use change and intensification (Figures 4.1c and d, and 4.2). At global scale, climate change causes a small increase in mean annual food production (Figure 4.1c) and slight decrease in the mean annual irrigation water demand (Figure 4.1d). The positive impact of climate change on production and water demand is caused by the effect of elevated CO_2 concentrations on water use efficiency of crops. The effect of CO_2 fertilization at high concentrations is still unclear and might be lower than simulated here due to nutrient limitations and other constraints (Ewert et al., 2007; Long et al., 2006; Tubiello et al., 2007) (See Annex A for additional discussion). Globally averaged, the CO_2 effect might offset the negative impacts of higher temperatures and precipitation changes (Figures 4.1c and d). However, climate change will still increase irrigation water demand in most of Europe, Australia and some parts of China and the USA (Figure 4.2).
Around the year 2000, about 60% of the global irrigation water demand was supplied from surface water (rivers and lakes 44% and reservoirs 16%), and 31% from groundwater. This indicates that 9% (386 km^3 yr^{-1}) of the total demand remained unfulfilled, resulting in an average loss of 67 Mt crops per year (table 4.1).

If groundwater extractions for irrigation will remain at current rates, the irrigation water

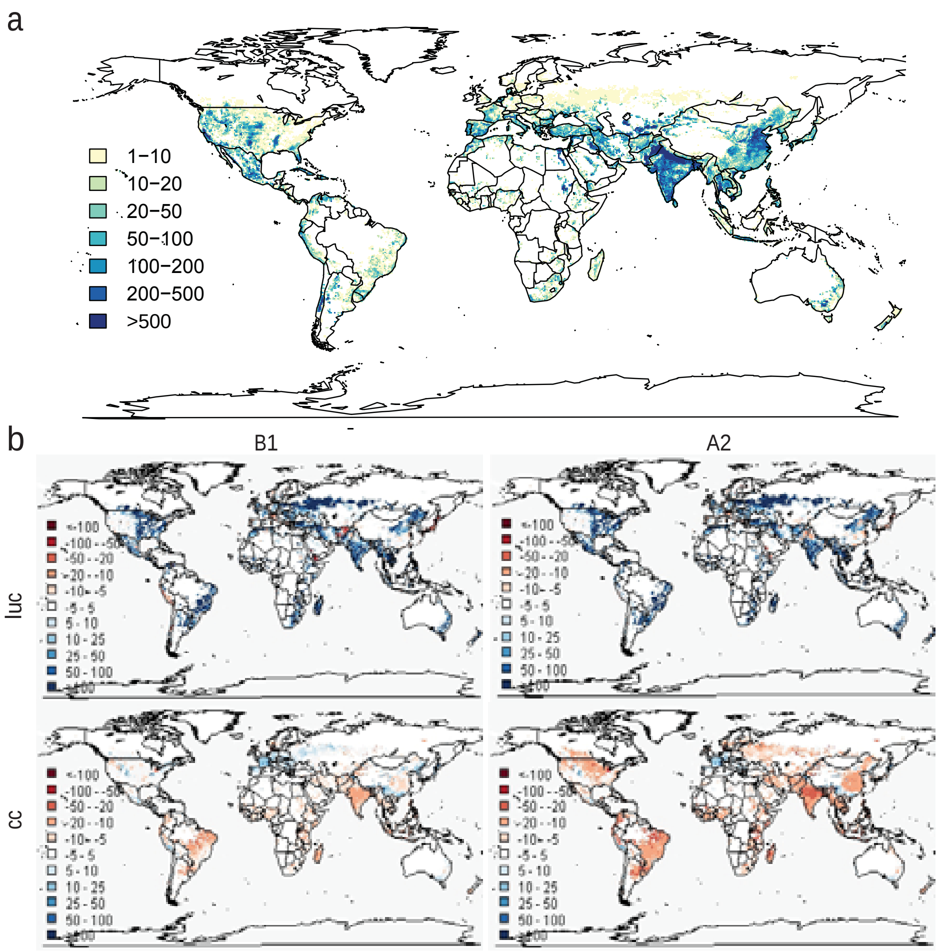


Figure 4.2 (**a**) current (1981-2000) annual irrigation water demand in mm averaged per 0.5 degree gridcell, (**b**) relative changes in irrigation demand due to land use change and yield increase only (upper), and climate change only (lower) for B1 and A2 (2081-2100 wrt. 1981-2000), all maps present average of simulations with 3 GCMs.

shortage will increase to 1184 $km^3\ yr^{-1}$ for the B1 scenario and 1384 $km^3\ yr^{-1}$ for the A2 scenario, by the end of the 21^{st} century. This is 23-27% of the total irrigation water demand (B1-A2). Consequently, 376-460 Mt or 19-20% (B1-A2) of the irrigated agricultural production will be lost (table 4.1). In terms of volume, this is almost a seven fold increase in production losses due to water shortage compared to the year 2000.

Climate change will have little impact on the total global water shortage and without climate change the water shortage would be even be higher (1258-1568 $km^3\ yr^{-1}$ for B1-A2). In some basins however, climate change is likely to increase crop losses. A large drop in water availability (Figure A2) will increase the water shortage and crop losses in e.g. the Grande de Santiago, Euphrates, Amu-Darya and Murray basins (figure A4).

Crop production losses will be relatively large in West Africa and South East Asia (Figure 4.3a and A3), where in some basins more than 50% of the required irrigated production cannot be achieved. Further analysis in selected river basins shows that the largest crop losses are expected in Zambezi, Krishna, Mekong and Irrawaddy river basins (Figure 4.3c). Not all of the new irrigated areas projected in *e.g.* the Rio Grande de Santiago, Parana, Niger, Zambezi, Irrawaddy, Mekong and Murray can be supplied with water (Figure 4.3b), which will result in lower crop production (Figure 4.3c). In basins that partly rely on groundwater for irrigation, a large part of production will still require similar groundwater volumes by 2100 e.g. in the Rio Grande de Santiago, Indus, Ganges, Krishna and Huang He (Figure 4.3b). Although part of the extracted groundwater is recharged annually, in those basins groundwater tables are observed to decline because withdrawals are larger than recharge (Qiu, 2010; Rodell et al., 2009). It is likely that further depletion will put a limit to extraction in those regions, causing further crop losses. Estimates of current global depletion of fossil groundwater resources are uncertain and vary between 27 and 283 km^3 $year^{-1}$ (Konikow, 2011; Wada et al., 2010a). Part of the 339-383 Mt (A2-B1) crop production that will depend on groundwater supply (table 4.1) can therefore probably not be achieved (Figure A3). However, there are also other regions where groundwater is not yet exploited and extractions can increase in the future (See Annex A for additional discussion).

Our results indicate that future food production as projected in recent agricultural scenarios will be severely limited by water availability. With the current irrigation efficiencies and storage capacity of large reservoirs, it will be impossible to supply enough water for all projected irrigated land. The agricultural scenarios therefore imply an overshoot of the planetary boundaries for freshwater use (Rockstrom et al., 2009). The most vulnerable regions will be South Asia and Southern Africa, where a rapid population growth and increasing living standards will cause a large increase in food demand. This increased demand cannot be produced with the available water resources. The different climate models and socio-economic scenarios used

Table 4.1. Total global water withdrawals from different sources and associated production of food crops. Numbers are the average of simulations using 3 GCMs

water source		irrigation water withdrawals (km^3 $year^{-1}$)			crop production (Mton DM $year^{-1}$)		
		current	A2	B1	current	A2	B1
rainfed		x	x	x	1623	3269	2535
irrigated	rivers and lakes	1718	1917	1992	565	1229	1088
	reservoirs	611	709	711	88	193	174
	groundwater as 2000	1192	1096	1180	239	339	383
	unavailable/lost	386	1384	1184	67	460	376
	total irrigated	3907	5107	5066	959	2221	2021
total		3907	5107	5066	2582	5490	4556

had surprisingly little impact on the overall results showing a very robust signal of future water limitation (Figures 4.1 & 4.3).

In order to guarantee sufficient food supply for future generations it is necessary to adapt agricultural planning and production. First of all there is a need to use the available water resources more efficient. Important irrigated areas of the world such as Mexico, Central Asia, India and China (Figure 4.2a) have very inefficient irrigation systems with losses over 60%. Large gains can be made by reducing the losses in these irrigation systems; e.g. by changing from surface to sprinkler or drip irrigation or from channel to pipeline conveyance. The creation of additional reservoir storage capacity can potentially increase water availability in regions with large inter-annual or intra-annual variability in precipitation. However, great care should be taken in developing new dams as they can potentially have large ecological and social impacts (WCD, 2000). Other options include transporting water from water-rich to water-poor regions (Stone and Jia, 2006) and desalinization (Elimelech and Phillip, 2011), although the costs and energy demands of desalination are probably too high for large scale implementation.

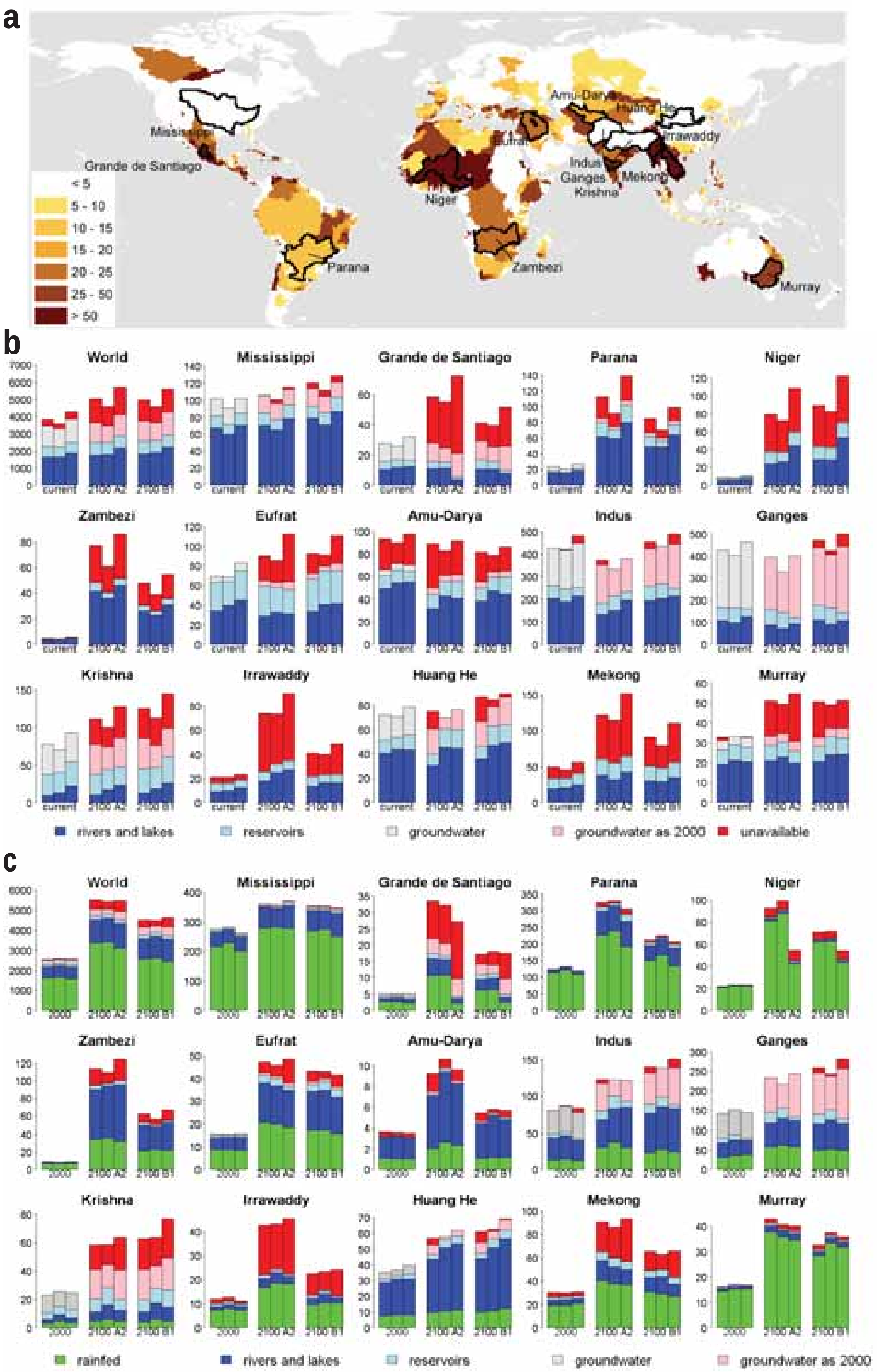
Our results clearly indicate that land use changes and intensification projected in global agricultural scenarios will not result into the required increase in food production due to severe shortages in irrigation water. Water availability should therefore be accounted for in the development of consistent and realistic agricultural scenarios. Furthermore it is important to develop agricultural systems which are much more water use efficient to secure more food with less water.

Acknowledgement

This reseach was supported by the Strategic Research Programme Global Food Security (KB1, 2011) of the Dutch Ministry of Economic Affairs, Agriculture and Innovation and by the Netherlands Environmental Assessment Agency.

Figure 4.3 (right page). Most vulnerable regions (**a**) Distribution of the mean annual losses in irrigated crop production due to irrigation water shortage for the A2 scenario (in % yr^{-1}) (2081-2100) (**b**) Irrigation water demand and availability in km^3yr^{-1}, globally and for a selection of river basins. Bars represent the current demand (1981-2000), and A2 and B1 scenarios (2081-2100). Colours show the potential fulfilment of this demand from different water sources: dark blue volumes can be extracted from natural rivers and lakes, light blue from human build reservoirs, grey from groundwater, pink from groundwater if supply can be sustained at current volumes, red volumes will be unavailable.

(**c**) As in (b) but for crop production in Mt yr^{-1}. Green volumes represent rainfed crop production, the sum of other colours represents irrigated production. Colours of water sources as in (b). Each group of bars represents simulations with 3 GCMs.


a
Mississippi
Grande de Santiago
Amu-Darya
Huang He
Irrawaddy
Eufrat
Indus
Ganges
Krishna
Mekong
Niger
Parana
Zambezi
Murray
< 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 50
> 50
b
World
Mississippi
Grande de Santiago
Parana
Niger
Zambezi
Eufrat
Amu-Darya
Indus
Ganges
Krishna
Irrawaddy
Huang He
Mekong
Murray
current
2100 A2
2100 B1
rivers and lakes
reservoirs
groundwater
groundwater as 2000
unavailable
c
World
Mississippi
Grande de Santiago
Parana
Niger
Zambezi
Eufrat
Amu-Darya
Indus
Ganges
Krishna
Irrawaddy
Huang He
Mekong
Murray
2000
2100 A2
2100 B1
rainfed
rivers and lakes
reservoirs
groundwater
groundwater as 2000

5

Climate change impacts on water availability in five South Asian river basins and potential of adaptation options – a modelling study

The Indian subcontinent faces a population increasing from 1.6 billion in 2000 towards 2 billion around 2050. Therefore, an expansion of agricultural area combined with yield increases will be necessary to still be able to produce the food needed in the future. However, with pressure on water resources already being high, and potential effects of climate change still uncertain, the question rises whether there will be enough water resources available to sustain this production. The objective of this study was to use a coupled hydrology and crop model to make a spatial explicit quantitative analysis of water availability for future food production in five South Asian basins (Indus, Ganges, Brahmaputra, Godavari and Krishna) in the absence or presence of two different adaptation options: an overall improvement of the irrigation efficiency and an increase of storage capacity of large reservoirs. It was found that the Godavari and Krishna basins will benefit most from an increased storage capacity, whereas in the Ganges and the Indus water scarcity mainly takes place in areas where this additional storage would not fill up completely. Increasing the irrigation efficiency will be beneficial in all basins, but mostly in the Indus and Ganges, as it decreases the pressure on groundwater resources and decreases the fraction of food production that would become at risk because of water shortage. A combination of both options seems to be the best strategy in all basins. The large-scale model used in this study is suitable to identify hotspot areas and support the first step in the policy process, but the final design and implementation of adaptation options requires supporting studies at finer scales.

Based on:

Biemans, H., L. Speelman, F. Ludwig, E. Moors, A.J. Wiltshire, P. Kumar, D. Gerten, P. Kabat (in revision). Climate change impacts on water availability in five South Asian river basins and potential of adaptation options – a modelling study. Science of the Total Environment

5.1 Introduction

The Indian subcontinent is a rapidly changing region where both climate change and socio-economic changes are expected to have a large impact on available water resources and food security. At this moment, India, Bangladesh, Nepal and Pakistan are home to almost 1.6 billion people and this population is expected to increase to over 2 billion in 2050 (UN, 2010). In addition, countries like India show a very high annual economic growth rate currently around 8% (ADB, 2011), which could continue to 2050 (Nakicenovic and Swart, 2000). Consequently, water demand for both the domestic and industrial sectors will rapidly increase (Amarasinghe et al., 2007; Gupta and Deshpande, 2004; Kumar et al., 2005).

To ensure food security for a larger and richer population, total agricultural production of food crops needs to increase. Projections of the future agricultural system show that suitable lands for agriculture are to a large extent already in production, which limits the scope for the expansion of area (Bruinsma, 2003; FAO, 2006). Still some expansion of rainfed and irrigated area is expected for this region (table 5.1). Consequently, increased production should also be established by an intensification of current agricultural area (e.g. by means of conversion of rainfed practices to irrigation or increasing crop rotations) and by other yield increases (e.g. by using improved crop varieties and better use of pesticides or fertilizers). The associated water demand of the agricultural sector is therefore also expected to increase.

The main sources of water for agriculture are direct precipitation, surface water available in rivers, lakes and reservoirs and groundwater. All these water sources are affected by climate change and the need for development of both food production and water resources is set against the need to simultaneously adapt to a changing climate.

The climate of the region is dominated by the Indian monsoon, which spans four months from June to September and is the major input of water into the region. Projections of climate change show a consistent warming, but a greater uncertainty in precipitation spanning a possible increase to decrease (Christensen et al., 2007; Moors et al., 2011). This uncertainty is associated with the wide range of simulated circulation patterns in the different global climate models (GCMs).

GCMs have too coarse spatial resolution to provide sufficiently detailed information for assessment of local impacts. Therefore Regional Climate Model (RCM) are used to downscale from global model projections to more detailed climate change projections.

Snow and glacier melt run-off from the Himalayas form an important contribution to the river flow in the Indus, Ganges and Brahmaputra river basins (figure 5.1). Climate change induced changes in the melt of glaciers and snow could significantly change the spring water availability in the headwaters of those rivers (Barnett et al., 2005; Immerzeel et al., 2010; Singh and

Bengtsson, 2004). The main determinant of water availability in South Asian basins however is monsoon precipitation, leading to a peak in discharge during the precipitation months of June to September. The Krishna and Godavari (figure 5.1) rivers are entirely rainfed, but also the three Himalayan basins show a very distinct seasonal pattern of streamflow, with about 80% of discharge being delivered during only four months of the year (GRDC, 2007).

Agricultural yields in whole India depend to a large extent on the amount of monsoon precipitation. Analysis of historical data shows that there is a strong correlation between the variability in total annual monsoon precipitation and crop yields (Kumar et al., 2004; Parthasarathy et al., 1988). Although this correlation is strongest for rainfed agriculture, also irrigated production shows a decline in years with low monsoon precipitation, because the shallow groundwater storage from which part of the irrigation water is drawn has not been completely replenished during years with low rainfall.

Groundwater is very important irrigation water supply, its contributions are estimated at 64% for India and 33% for Pakistan (Siebert et al., 2010). However, groundwater levels are already declining in India (Molden et al., 2002; Rodell et al., 2009; Wada et al., 2010b). Therefore, extractions probably cannot be continued at present rates and groundwater might not be expected to be a reliable water source to sustain future agricultural production.

As illustrated in the previous paragraphs, a complex interplay of multiple factors are determining the future of the water resources situation in this region. To understand the interactions

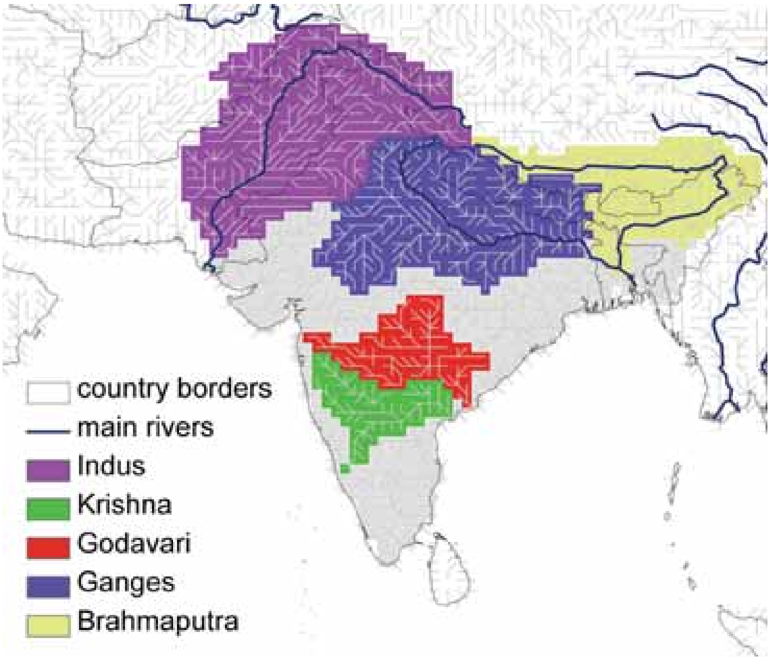


Figure 5.1. Location of the five study basins and illustration of the river topography at 0.5° resolution.

between the processes and allow for future projections, simulation models are needed that capture the processes described above including their linkages and feedbacks.

Questions of particular concern are whether there will be enough water resources available to fulfill the growing demand under a changing climate, and what adaptation strategies might prevent or reduce water scarcity. There is a need for quantitative tools to evaluate the effects of potential adaption strategies. (Aggarwal et al., 2004; Wilby et al., 2009).

The objective of this study is to make a spatially explicit quantitative analysis of water availability for food production in five South Asian basins in the absence or presence of two different adaptation options: an overall improvement of the irrigation efficiency, and an increase of the storage capacity of existing large reservoirs. Based on this, it identifies regions where these adaptation options will be the most beneficial. A second objective is to explore the suitability of a large scale hydrology and vegetation model for the quantitative evaluation of adaptation measures.

5.2 Material and methods

5.2.1 LPJmL model

The model used in this study is the coupled hydrology and dynamic vegetation model LPJmL (Bondeau et al., 2007; Sitch et al., 2003). LPJmL integrates a representation of the coupled terrestrial hydrological cycle and carbon cycle, which makes it a very suitable tool to study the relationship between water availability and crop production. Several components of the water and carbon cycles are validated and tested: e.g. river discharge (Biemans et al., 2009, chapter 2; Gerten et al., 2004), crop yields (Fader et al., 2010), irrigation requirements (Rost et al., 2008), and sowing dates (Waha et al., 2012). A validation specifically or the region is presented in the first part of the results section.

LPJmL explicitly accounts for human influences on the hydrological cycle, e.g. by including algorithms for irrigation extractions and supply (Rost et al., 2008) and the operation of large reservoirs. It simulates both changes in streamflow due to reservoir operation and water supply from reservoirs to the irrigated fields (Biemans et al., 2011, chapter 3).

Net irrigation water demand for irrigated crops is calculated as the minimum of the amount of water needed to fill the soil to field capacity and the amount needed to fulfill the atmospheric evaporative demand (Rost et al., 2008). Subsequently, the gross irrigation demand (withdrawal demand) is calculated by multiplying the net irrigation water demand with a country specific efficiency factor (Rohwer et al., 2007). Part of the withdrawn water is lost during conveyance from the withdrawal point to the irrigated field according to a country specific conveyance efficiency factor (Rohwer et al., 2007). Water is withdrawn from local surface water if available

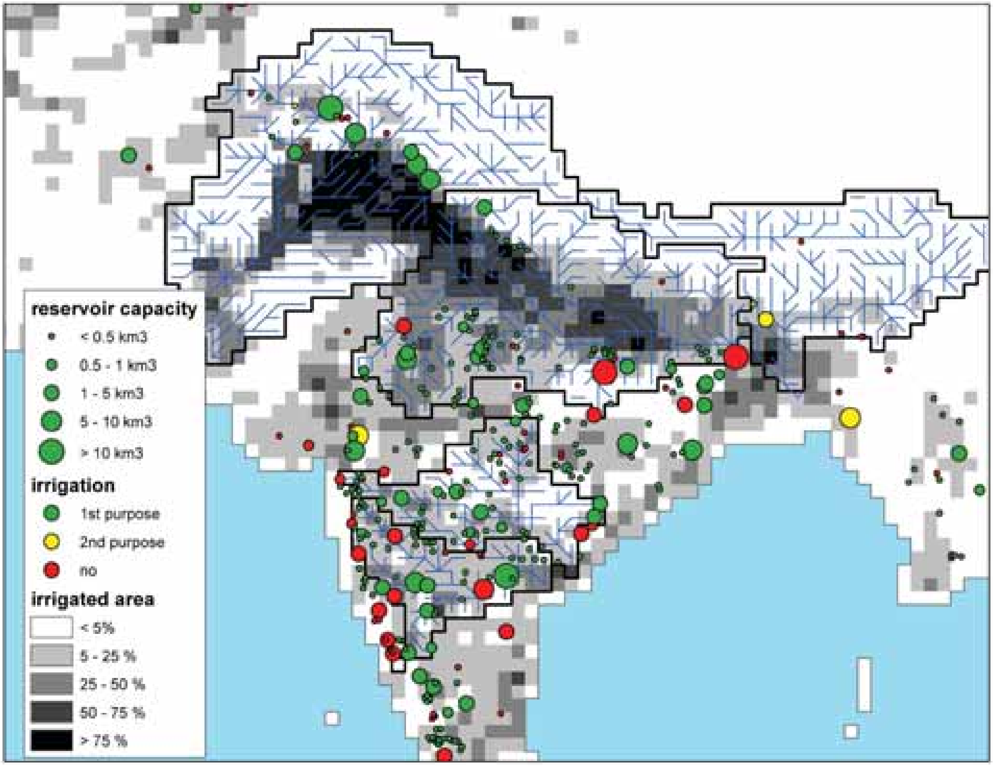


Figure 5.2. Locations of dams relative to irrigated areas. Points: all dams that are implemented in the model; colors show whether the reservoir is used for irrigation, the size refers to the capacity of the reservoir. Grey shades: the percentage of the cell that is irrigated according to the land use input. Blue lines: STN30 river network at 0.5 degree, determining the delineation of river basins in black lines.

(rivers and lakes), and subsequently from surface water in the neighboring cell, an artificial reservoir with irrigation purpose if within reach and an non-restricted other source, which is most probably groundwater (for a more detailed description of the irrigation algorithm, see Biemans et al., 2011; Rost et al., 2008, chapter 3).

Crop growth is calculated based on daily assimilation of carbon in 4 pools: leaves, stems, harvestable storage organs and roots. Carbon allocated to those pools depends on the phenological stage of the crop and adjusted in case of water stress on the plants. Crops are harvested when either maturity or the maximum number of growing days is reached (Bondeau et al., 2007; Fader et al., 2010).

The model has been applied to study the effect of climate change on water availability and requirements for food production at global scale (Gerten et al., 2011);(Falkenmark et al., 2009); (chapter 4), and the potential of rainfed water management options to raise global crop yields (Rost et al. 2009).

Figure 5.2 shows the set-up of the model for the study region. The five basins are represented by a simplified river network at 0.5 degree resolution (Vörösmarty et al., 2000a), the land use

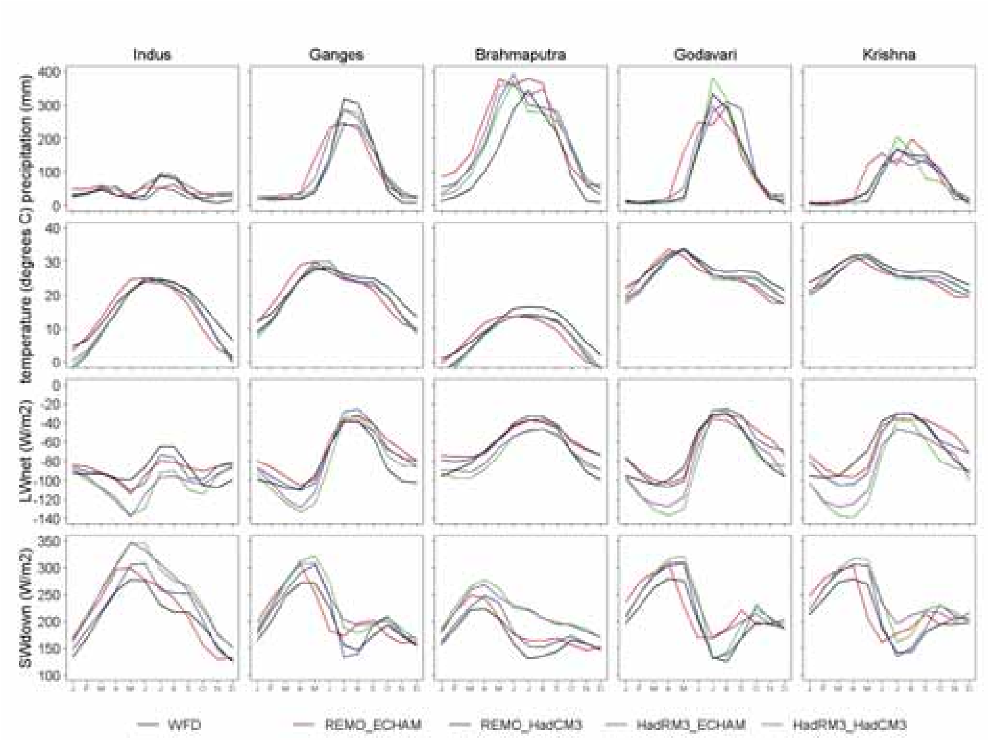


Figure 5.3. 1971-2000 mean monthly precipitation, temperature, net longwave radiation and shortwave downward radiation simulated by 4 RCM simulations compared to observations (Weedon et al., 2011).

by gridcell fractions of both irrigated and rainfed crops in 2000. Locations of large dams, the storage capacity in their reservoirs and operation purpose are taken from the GRanD database (Biemans et al., 2011, chapter 3; Lehner et al., 2011). The total cumulative storage capacity in reservoirs differs per basin (table 5.1).

5.2.2 Climate change scenarios

For a topographically complex region like the Himalayas, where orographically induced precipitation prevails, regional climate models (RCMs) usually provide better simulations of observed climate than global climate models (GCMs). Specifically the simulation of spatial patterns of summer monsoon is improved by using RCMs to downscale GCM projections (Rupa Kumar et al., 2006). In this study RCM runs from the EU HighNooN project (www.eu-highnoon.org) are used to downscale from global model projections to 0.25 degree. The GCMs HadCM3 (Gordon et al., 2000) and ECHAM5 (Roeckner et al., 2006) for the SRES A1B scenario are used to drive two RCMs; HadRM3 and REMO (Jacob, 2001; Jacob, 2009). HadRM3 is based on the HadAM3 model described by Pope et al. (2000) including the MOSES 2.2 land surface scheme (Cox et al., 1999). The two GCMs are chosen for their ability to simulate the present monsoon dynamics and the ensemble of RCMs to incorporate a measure of uncertainty in the

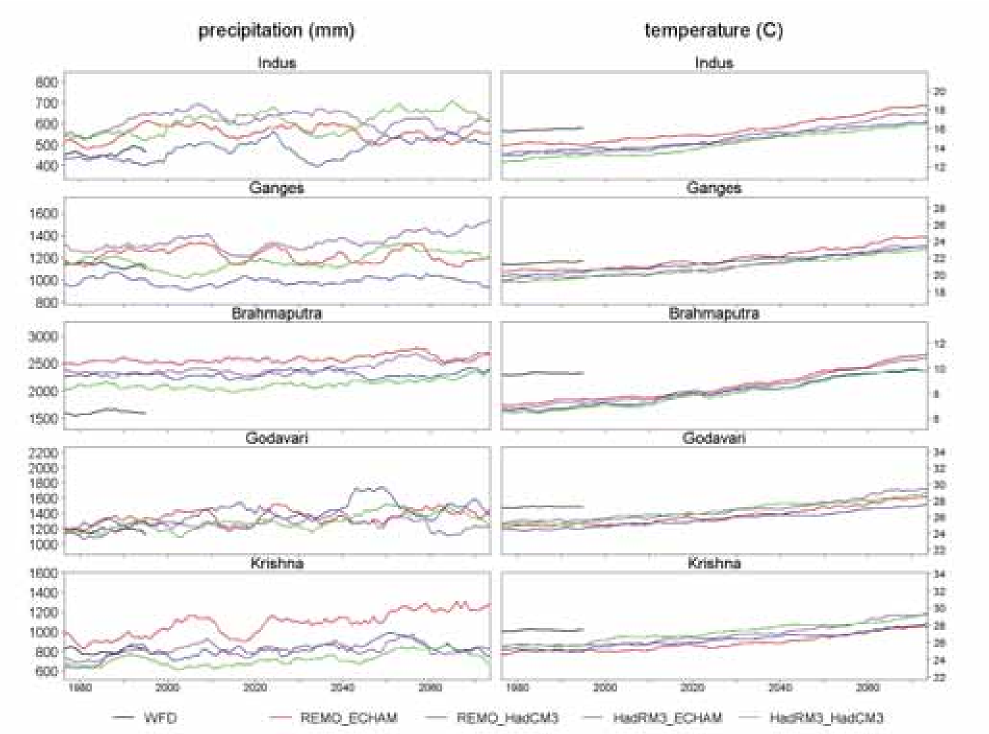


Figure 5.4. Ten-year running mean average annual precipitation and temperature projections from the RCM simulations and observations (Weedon et al., 2011).

downscaling and in the representation of regional processes (Moors et al., 2011).

The periods 1971-2000 and 2036-2065 are used in this study to represent the present climate and future climate respectively. Despite the uncertainty in the downscaling process (Lucas-Picher et al., 2011) and the difficulties many GCMs have in simulating the monsoon dynamics, the ensemble is able to capture the mean climate during the control period for the 5 river basins (figure 5.3). Here, RCM-simulated mean monthly climate is compared with an estimate of observed climate provided by the WATCH forcing data (WFD) (Weedon et al., 2011).

The RCM simulations reveal uncertainty in how the future climate will evolve. Climate models simulations agree on a warming trend in South Asia, whereas precipitation projections for this region tend to disagree (Christensen et al., 2007). By using 4 different RCM runs a measure of uncertainty is included as needed in the design of robust adaptation strategies (figure 5.4).

LPJmL is forced with the time series of the RCM output variables temperature, precipitation, longwave net radiation and shortwave downward radiation and with annual global average CO_2 concentrations according to the SRES A1B scenario (Nakicenovic and Swart, 2000). The RCM output at 0.25 degree is aggregated linearly to 0.5 degree resolution to be compatible with the land use information used.

5.2.3 Land use change scenarios

Land use change scenarios used here were developed by the International Institute for Applied Systems Analyis (IIASA) using their Global Agro-Ecological Zones model (GAEZ) (Fischer et al., 2005; Fischer et al., 2007). Projected changes in agricultural area are a result of a series of simulations taking into account scenarios of population growth, economic developments and associated food demand, suitability of land for conversion into agricultural land and the potential for yield increases on current cropping areas. Spatial explicit water availability is not taken into account in the development of scenarios. The scenario used in this study is derived from a global-scale land use change scenario which was developed as part of the EU WATCH project (www.eu-watch.org) and provides fractions of rainfed and irrigated cropping area for each 0.5 degree grid cell for A2 and B1 storylines. Land use scenarios that explicitly account for the expansion of both rainfed and irrigated cropping area at grid level do not exist for the A1B scenario. Therefore the land use scenario used here is based on A2 storyline assumptions. Although global population projections for A1B are lower than for A2, economic growth is projected to be much higher in A1B then in A2 (Nakicenovic and Swart, 2000). Further, land use scenarios for A2 and B1 for this region are very similar up to 2050 (table 5.1). Therefore, we judge it legitimate to A2 land use change scenario for this study. Table 5.1 summarizes the land use changes projected for the 5 study basins, for A2 and B1.

The total rainfed and irrigated cropping area per grid cell is disaggregated to fractions of crop types by using the crop distributions provided by Fader et al. (2010), which are a combination of crop-specific distributions of MIRCA2000 (Portmann et al., 2010) and cropland extent data from Ramankutty et al. (2008a). Because the land use change scenarios from IIASA do not provide crop specific information, shares of individual crops were taken from Fader et al. (2010) and assumed to remain constant in the future.

5.2.4 Model runs

5.2.4.1 Simulations

To bring the carbon (in soil and vegetation) and water pools (in soil and surface water) into equilibrium, a spin-up of 1000 years is made by forcing LPJmL repeating daily climate input of 1960-1999 of the WATCH forcing data (WFD) (Weedon et al., 2011) and assuming an unlimited water supply on irrigated areas.

In addition to water available in the soil, LPJmL distinguishes three sources of water to withdraw from to the extent required by crops while accounting for irrigation efficiencies *cf.* (Rohwer et al., 2007): natural rivers and lakes, human-built reservoirs, and an unlimited other source (deep non-renewable groundwater, inter-basin transfers, etc.) assumed to be tapped when the other sources are depleted (representing the “IPOT” simulation in Rost et al. 2008). To estimate the individual contributions to withdrawal from these water sources and the corresponding part

Table 5.1. Aggregated rainfed and irrigated cropping area per basin in 2000 and 2050 for B1 and A2 (Fischer et al. 2007), and total reservoirs capacity used for irrigation purposes in 2000.

	Rainfed (1000 km^2)			Irrigated (1000 km^2)			Reservoir capacity (km^3)
	2000	2050 B1	2050 A2 (Δ%)	2000	2050 B1	2050 A2 (Δ%)	2000
Indus	129	127	126 (-2.3)	213	220	208 (-2.3)	45.0
Ganges	285	256	259 (-9.1)	257	291	287 (11.6)	25.4
Brahmaputra	69	61	65 (-6.8)	27	35	36 (33.4)	1.8
Godavari	123	131	131 (6.5)	32	48	47 (46.6)	18.0
Krishna	114	104	106 (-7.3)	40	65	66 (65.8)	31.0

of crop production, four simulations were needed. For each of these simulations an additional 150 years of spin-up is performed to adjust the water pools to the specific model settings.

A first simulation assumes purely rainfed conditions, i.e. water for agriculture is only provided by precipitation (INO). In a second simulation, irrigation withdrawal is restricted to the water available in natural lakes, rivers and renewable groundwater stores (ILIM). A third simulation also accounts for water withdrawn from artificial reservoirs built with an irrigation purpose (IRES). And fourth, we performed a simulation in which the irrigation water supply is not restricted to the available water resources, implicitly assuming access to fossil groundwater, or river diversions (thus implying an upper estimate of crop production) (IPOT).

This set of simulations is performed for each of the four different RCM climate simulations, and for the recent, i.e. 1971-2000 climate and 2000 land use (A), as well as for the 2050s, i.e. 2036-2065 climate and 2050 land use to assess the ‘baseline' situation (B).

5.2.4.2 Adaptation options

In addition to the baseline assessment (B), this study evaluates the effect of three different sets of adaptation options:

i. Reservoirs are an important contributor to irrigation water supply (Biemans et al., 2011, chapter 3). Because river discharge in South Asian basins is very variable due to monsoon precipitation, creating extra capacity to store water could prevent water scarcity by creating a buffer for dry periods. In the model implementation of this adaptation option, the capacity of existing reservoirs is simply doubled (C).

ii. An increase in the efficiency of the irrigation system to current efficiencies in Western Europe. The current average efficiency of the irrigation systems in India, Nepal and Bangladesh is estimated at 37.8% and in Pakistan 29.4% (which means that the extracted water is about 2.5 to 3.5 time the amount actually needed by the plant), with conveyance loss alone reaching about 30% of the water withdrawn (Rohwer et al., 2007). Implementation of this adaptation option would increase the total efficiency in 2050 to 71.3%, and conveyance losses to only 5%, which is the efficiency currently reached in countries in Western Europe (Rohwer et al., 2007). In practice, this would indicate a shift from the presently prevailing surface irrigation to micro-irrigation systems, and a transport through pressured pipelines instead of open channels (D).

iii. Both measures combined (E).

5.2.4.3 Evaluation indicators

To assess the impact of climate change and land use change on water scarcity in the study basins, and to evaluate the potential impact of adaptation options, a set of indicators calculated for all simulations is used. The first indicator is the basin-aggregated total irrigation water demand and the shares of this demand that can be met by the different water sources. A second indicator at basin scale relates the water taken from different sources to total crop production. It shows which part of the potential harvest will be lost if the required water extracted from a source is unavailable.

The third indicator denotes agricultural water stress, defined here as the fraction of total irrigation water demand that cannot be met by renewable water. Maps of this indicator show the heterogeneity throughout the basins and can therefore be used to identify current or future hotspots of water scarcity and, respectively, dependence on non-renewable water. They also show where adaptation measures potentially have the strongest effect.

5.3 Results

5.3.1 Validation

Irrigation withdrawal estimated using LPJmL for India and Pakistan are higher than withdrawals reported by FAO on AQUASTAT (table 5.2). The difference between current estimates with LPJmL and previous estimates using the same model by Rost et al. (2008) can be explained by the use of another land use set, and therefore other total irrigated area in both countries, use of a different climate forcing in this study and several small model adjustments. Wisser et al. (2008) have already shown the large variations in estimates caused by using different land use and climate data sets.

According to this validation, LPJmL overestimates discharge in all basins except the Brahmaputra basin. Biemans et al. (2009, chapter 2) showed high variations in simulated discharge caused by forcing with different precipitation estimates, which are very uncertain for this region. Therefore, over and underestimations might partly be explained by errors in the precipitation input data.

LPJmL yields are calibrated with FAO reported yields. Here it is showed that FAO yields can be

Table 5.2. Estimates of irrigation water withdrawal, discharge, yields and irrigation efficiency for the region under study, as calculated with LPJmL, using WATCH forcing data (Weedon et al., 2011), and estimates provided by others.

Variable	Area	LPJmL simulated	Other estimates	Period
Irrigation water withdrawal ($km^3\ yr^{-1}$)	India	803.5	558.4[a], 710-715[b], 317[c]	1998-2002[a], around 2000[b,c]
	Pakistan	286.1	162.7[a], 117-120[b], 117[c]	1998-2002[a], around 2000[b,c]
discharge ($m^3\ s^{-1}$)	Ganges - Farakka	19409.6	12474.1[d]	1971-1979
	Brahmaputra - Bahadurabad	20977.1	23718.8[d]	1986-1991
	Godavari - Polavaram	5626.4	2533.2[d]	1971-1979, 1975 missing
	Indus - Kotri	2654.4	2396.1[d]	1976-1979
Wheat yield ($t\ ha^{-1}$ DM)	India	2.5	2.19609[e]	1991-2000
	Pakistan	1.8	1.8236[e]	1991-2000
Rice yield ($t\ ha^{-1}$ DM)	India	2.5	2.43636[e]	1991-2000
	Pakistan	2.4	2.37379[e]	1991-2000
Irrigation efficiency (%)	India	37.8	30-40[f], 40-70[g]	1994[f], 2010[g]

a AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm)
b Rost et al. (2008)
c Siebert et al. (2010), but note that these last numbers are estimates of consumptive water use, and should be multiplied with the irrigation efficiency to estimate withdrawals.
d GRDC (http://www.bafg.de/GRDC)
e FAOSTAT (http://faostat.fao.org)
f Sivanappan (1994)
g Gupta and Deshpande (2004), estimate for 2010, distinguished between surface water (40%) and groundwater (70%)

reproduced by tuning management parameters within plausible ranges, and without losing consistency in the simulation of physical processes.

The estimated irrigation efficiency applied in LPJmL is in agreement with other estimates.

5.3.2 Aggregated water demand and availability from different sources

The difference in simulated irrigation water demand between the 5 South Asian basins is very large (figure 5.5). The largest amount of water is withdrawn in the Indus and Ganges river basins, where current extractions are estimated to be 467 and 375 $km^3\ yr^{-1}$ (average of 4 RCM runs). In the Godavari and Krishna basins the simulated mean annual extractions are 64 and 81 $km^3\ yr^{-1}$. The estimated irrigation withdrawals in the Brahmaputra basin are relatively small, 28 $km^3\ yr^{-1}$, which can be explained by its relatively small irrigated area (table 5.1) due to the large part of this basin that is at high elevation.

The availability of water resources is also very different between those basins; in the Brahmaputra almost all water demand can be fulfilled by extractions from surface water (natural rivers, lakes, recharged groundwater and artificial reservoirs, which are regarded as renewable resources), whereas the other basins seem to be more water scarce as only 78%, 44%, 36% and 60% of the total irrigation water demand can be fulfilled by surface water for the Indus, Ganges, Godavari and Krishna basins, respectively. This means that annually for the five basins, a cumulative volume of 392 $km^3\ yr^{-1}$ of irrigation water has to be extracted from other sources, which is mainly deep groundwater.

In all basins, reservoirs play an important role in the supply of irrigation water, as they

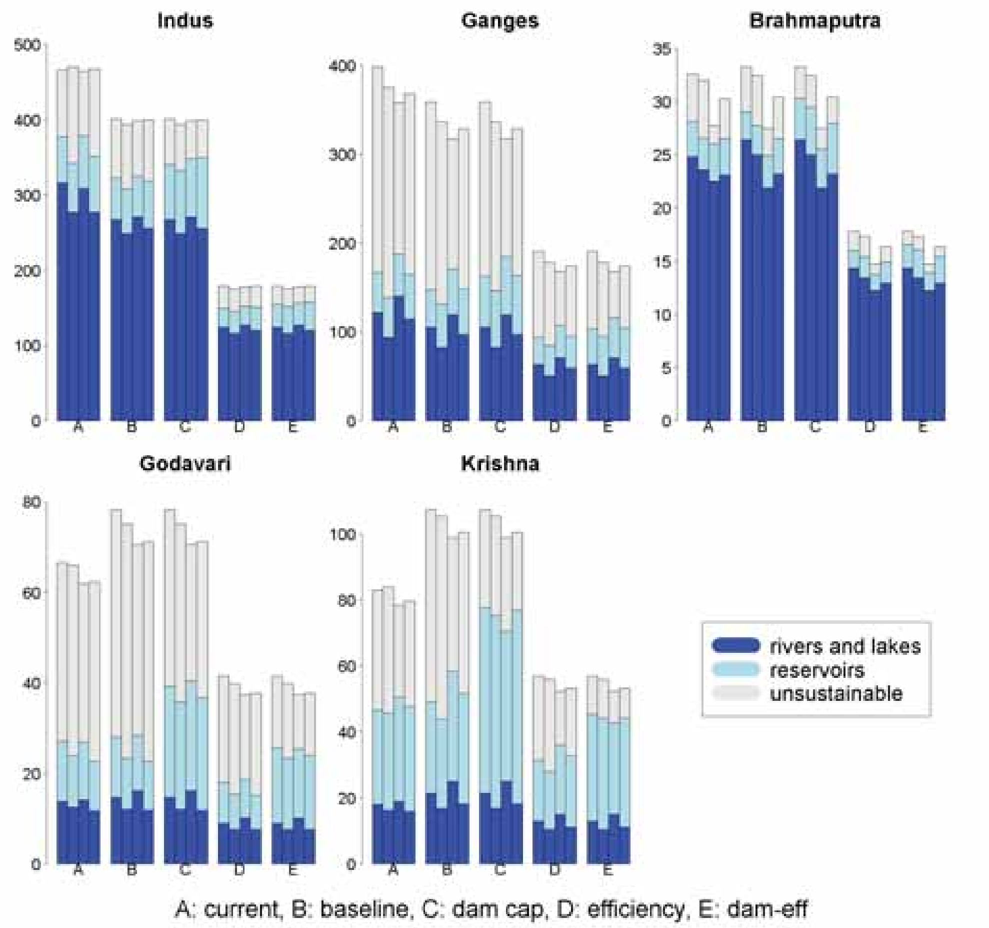


Figure 5.5. Contribution of water sources to fulfill irrigation water demand. Mean annual gross irrigation demand in km^3 and its sources of supply for all five study basins. Results are shown for present (i.e. 1971-2000) climate and year 2000 landuse (A), and for the future (i.e.2036-2065 climate and 2050 land use) for the baseline situation without adaptation (B), doubled reservoir capacity (C), improved efficiency (D) and a combination of the two latter (E). Four adjacent bars show the results simulated by four RCMs (REMO-Echam, REMO-HadCM3, HadRM3-Echam and HadRM3-HadCM3, respectively). Note the different scales for different basins.

redistribute the water in time and space. The Krishna river basin gains the most from its reservoirs in relative terms, as 37% (30 km^3 yr^{-1}) of irrigation water is extracted from existing reservoirs. In absolute terms, in the Indus basin most water is supplied from reservoirs; 67 km^3 yr^{-1}, which is however only 14% of the total demand.

In the baseline scenario (B), LPJmL projects a decrease in annual irrigation water demand in the Indus and the Ganges, which can be explained by the increasing CO_2 concentration, causing plants to use water use more efficiently (Ewert et al., 2007; Long et al., 2006). This partly compensates for potential negative effects of changes in other climate variables, particularly the overall warming and the regional shifts in precipitation (see figure 5.4). In the Indus basin, a small decrease in total irrigated area amplifies the declining demand caused by CO_2 increase, whereas in the Ganges basin the net effect of climate change, CO_2 rise and irrigation expansion is only a small decrease in demand. Only in the Godavari and Krishna rivers a relatively large increase in irrigated area will cause a net increase in irrigation water demand.

A doubling of the capacity of existing reservoirs (C) would increase the surface water supply substantially in the Godavari and Krishna basins. This indicates that in those basins, water scarcity is mainly a problem of distribution of water, and that the absolute annual available amount would be sufficient if the current system of reservoirs was well located in reach of the irrigated areas. In those basins, increasing the total storage capacity could partly relieve water stress caused by over-extraction of groundwater. In the other basins, increasing the storage would increase surface water extractions, but relatively less, e.g. because the total reservoir capacity is smaller relative to the total water demand.

Although an increase in the overall efficiency of the irrigation system (D) would not significantly change the fraction of irrigation water demand that can be supplied from surface water in all basins, the total volume and especially the volume of groundwater extractions would decrease and therefore reduce the rate of groundwater depletion significantly.

As can be expected, a combination of both adaptation options (E) would reduce water stress the most, mainly in the Godavari and Krishna basins (figure 5.5).

Although there is a spread amongst the results simulated by different ensemble members, the climate change signal is robust. This suggests that the demand-driven changes in total water requirements are a more important factor determining future water stress than climate change alone.

5.3.3 Food production at risk

Figure 5.6 shows the disaggregation of the total crop production to the different sources of water. More than 60% of the crop production in the Brahmaputra basin is rainfed, while in the Indus, more than 90% of all crops are produced on irrigated lands. In the Ganges, Godavari and Krishna basins, rainfed production is still substantial and provides 23%, 35% and 25 % of the total production, respectively.

In all basins, except for the Brahmaputra, a large part of the total crop production depends on water withdrawn from deep groundwater or other unsustainable sources (figure 5.6). This part of the crop production could become at risk, because it cannot be produced if the needed volumes of water (figure 5.5) cannot be supplied. Since the groundwater tables are already declining (Rodell et al., 2009), it is not unrealistic that this will happen. In all basins the fraction of crop production at risk would decline after implementation of adaptation measures (figure 5.6).

5.3.4 Spatial distribution of water shortage

The most water-scarce regions will be located in the southeastern parts of the Indus region, the southwestern part of the Ganges basin and the western parts of the Godavari and Krishna basins (figure 5.7). In the Godavari and Krishna basins, doubling of storage capacity has the

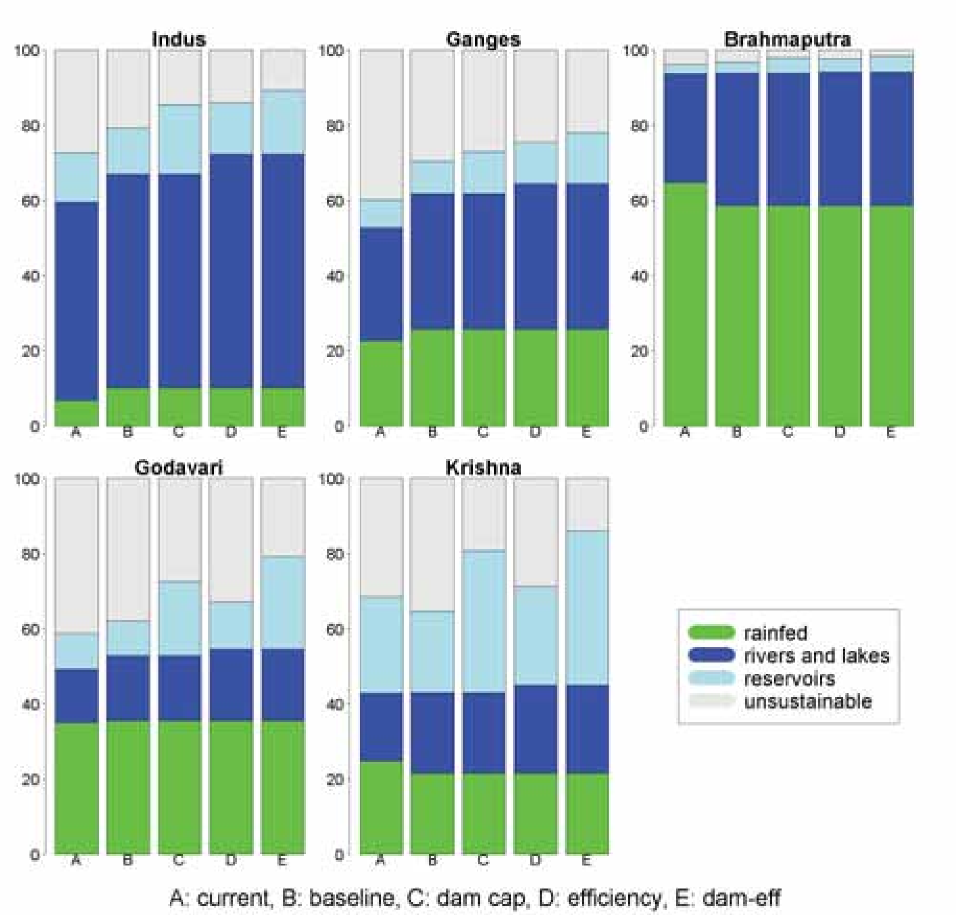


Figure 5.6. Attribution of crop production to water sources. Ensemble mean annual contribution of water sources to total crop production for all five study basins. Other details as in figure 5.5.

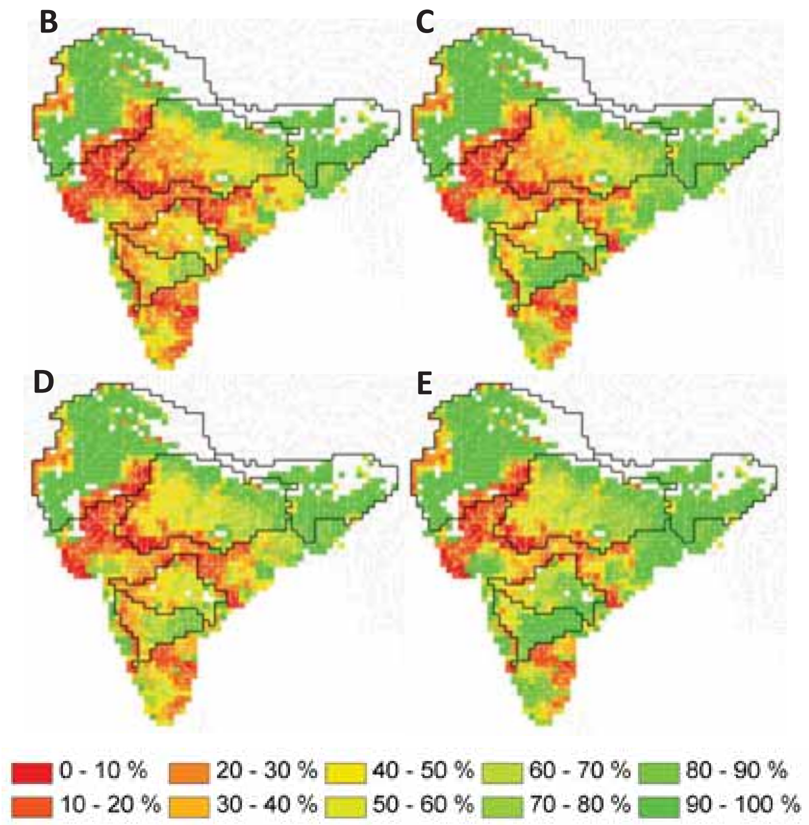


Figure 5.7. Spatial distribution of water scarcity: percentage of irrigation water demand that can be fulfilled by water extractions from natural lakes, rivers and reservoirs in baseline (B) and after the implementation of adaptation measures increased reservoir capacity (C), improved irrigation efficiency (D) and a combination of both measures (E). Figure based on mean of ensemble results.

largest effect, but still leaves some areas in the most upstream (north west) parts of the basins in a water-scarce status. The gains in the Ganges basin would be largest under improved irrigation efficiency. Further, it is suggested that in certain areas, e.g. in the southern part of the Ganges basin, the presented options would not be suitable to reduce water scarcity (see D and E simulations).

5.4 Discussion

This study demonstrates the effect of climate and land use changes on water availability and demand in five South Asian river basins, both in a 'baseline' situation without any adaptation in agricultural water management and in a situation after doubled reservoir storage capacities and optimized irrigation efficiencies. It further shows how a large scale hydrology and crop model can be used for a quantitative evaluation of adaptation measures.

Although it is not unexpected that an increase in irrigation efficiency will lead to a decrease in water demand and an increase in storage can relieve scarcity in some areas, the model applied here helps identifying regions where water scarcity is most pronounced. The model shows the spatial distribution of the effects of adaptation measures. By combining the effects of climate change and land use change in an integrated analysis, it is possible to simulate a complex system including interlinkages and feedbacks. Using the model in combination with scenarios for both climate and land use change, gives the possibility of evaluating a whole suite of potential adaptation measures, and can support policy makers with first indications on the best (combination) of measures.

In 2000 the population of India was 1 billion people and according to different scenarios its population will have grown towards 1.4-1.8 billion by 2050 (Grubler et al., 2007; UN, 2010). The resulting increase in food demand can only be fulfilled if the agricultural area is expanded and higher yields will be achieved. Figure 5.5 showed that in the Ganges, Godavari and Krishna basins, irrigation water supply is to a large extent depending on unsustainable groundwater supply and still will be in the future under baseline conditions. In those basins, around 40% of the total crop production can be attributed to groundwater, and this production would be lost without its supply (figure 5.6). Since groundwater exploitation already is a major concern in large parts of India (Rodell et al., 2009), it is very important to decrease both its extractions in terms of volume, as well as the fraction of food production that is at risk. The suggested adaptation strategies could help decreasing groundwater extractions, and at the same time reducing the fraction of food production potentially lost. Although an increase of storage capacity will not be achieved by doubling existing reservoirs, but rather by building new ones, and improving the irrigation efficiency can only happen slowly, by replacing existing irrigation systems, both options are included in the Government of India's Five Year Plan (GOI, 2007). From our study it can be concluded that while improving irrigation efficiency will be beneficial in all basins at all locations, increasing storage capacity will only be beneficial if there is enough water available during the year.

However, it has to be noted that there are still many uncertainties related to the presented results. For example the spread amongst simulated precipitation amongst the RCM runs is large. Because uncertainty in *observed* precipitation is also large, especially in topographically complex regions (Biemans et al., 2009, chapter 2), it is difficult to judge which of GCM-RCM combinations performs best in simulating the current climate. Further, uncertainty in precipitation input is often translated into an even higher uncertainty in simulated discharge (Biemans et al., 2009, chapter 2), therefore the simulated water availability for irrigation is very much dependent on the climate dataset used.

The mean annual temperature is somewhat underestimated by all GCM-RCM combinations (figure 5.4), mainly caused by an underestimation of temperature in winter months (figure 5.3).

Further, the presented study uses climate input to force a hydrology and vegetation model which is a one-way coupling. In reality, feedbacks between the (changing) land use and the climate exist. For example, an increase in irrigated area might influence future precipitation patterns (e.g. Tuinenburg et al., 2010).

LPJmL was forced with annual global average CO_2 concentrations according to the A1B scenario (Nakicenovic and Swart, 2000). Plants are known to become more water-efficient under a higher CO_2 concentration, but the strength of this process in the field is still uncertain (Ewert et al., 2007; Long et al., 2006). The model uses a photosynthesis algorithm that accounts for the effect of CO_2 fertilization without any leveling off at higher concentrations (Sitch et al., 2003). Therefore, the efficiency of water use simulated by the model might be too optimistic, and hence the actual water demand in 2050 could be higher than simulated. Further, LPJmL-simulated crop production is only limited by climate and water supply, and does not account for the negative effects of e.g. nutrient limitation, soil erosion or diseases (Bondeau et al., 2007).

Modeled yields are calibrated by tuning management parameters using a method described by Fader et al. (2010). Those management parameters are calibrated based on FAO statistics at country scale. Any within-country heterogeneity or even within-region heterogeneity in crop yields caused by management practices, crop varieties or economic factors like farm size are therefore not represented in the model. Consequently, differences in regional or local water demand caused by these heterogeneities are not accounted for.

Any scenarios on future changes in management, cropping intensity or crop varieties are not taken into account in this simulation, because the calibrated management parameters are not adjusted during the simulation. Besides an expansion of the current cropping area, the future food production requirements can only be reached if higher yields can be established by using other management practices or varieties (Bruinsma, 2003; FAO, 2006). Potentially this will lead to a higher water demand than currently projected in the simulations.

Although agriculture was and probably will be the largest water user, the water extractions for the domestic and industrial sectors are projected to grow substantially (e.g. Gupta and Deshpande, 2004) (Bhadwal et al., submitted). Therefore, a next step in the integrated analysis would require to account for the withdrawals from these sectors as well, as there might be areas of conflict between different water users.

This study showed a small selection of adaptation measures and was therefore limited. A more complete assessment should evaluate the effect of more options, e.g. rainwater or runoff harvesting (e.g. as in Rost et al., 2009; Wisser et al., 2010), different land use patterns, or cultivation of other crops or crop varieties.

Finally, the model simulations are giving more insight in the potential effect of adaptation measures, but provides those insights only at a rather coarse scale: at 0.5 degree resolution and implemented for the whole basin. The tool used here is very suitable to quickly scan and evaluate the effects of a series of different adaptation strategies under different climate and land use scenarios. It does support the first step in the policy process, but more detailed models are needed to support the final design of adaptation strategies.

5.5 Conclusions

This study showed the potential effect of a selection of adaptation measures on the water resources availability and demand in five South Asian study basins. There are several limitations to the study regarding the level of detail of the implementation, the simplification or neglecting of certain processes and the selective set of adaptation measures studies. Still some important conclusions can be drawn based on the results.

Some basins have more potential to gain from adaptation options than others. From the five basins that were used in this study, it was found that the Brahmaputra probably will not face large water scarcity in 2050. From the other basins, Krishna and Godavari seem to have the highest potential to improve their water resources situation by implementing water saving adaptation measures such as increasing the irrigation efficiency or increasing the storage capacity in large reservoirs. Based on this study, a combination of both options seems to be the best strategy.

A coupled hydrology and crop model like LPJmL is suitable to study the combined impacts of climate change and socio economic changes, and the effects of certain adaptation measures. Simulation results can be used as a first scan to inform policy makers in a quantitative manner on the potential futures of a region. We note though, that while the large-scale model used here is suitable to identify hotspot areas and interlinkages and feedbacks between processes and regions, the final design and implementation of adaptation options requires supporting studies at finer scales.

Acknowledgements

This work has been supported by the HighNoon project funded by the European Commission Framework Programme 7 under Grant Nr. 227087 and by the Netherlands Environmental Assessment Agency. A. Wiltshire was partly supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101).

6

General discussion

6.1 Introduction

The general objective of this thesis is to assess the combined effect of future socio-economic and climate changes on agricultural water supply and demand, as well as the associated effects on crop production towards 2100. Therefore it was first needed to validate simulated discharge for many river basins (chapter 2) and improve the model with an algorithm for reservoir operation (chapter 3).

In addition to changing the timing of river flow, water from reservoirs currently fulfils about 17% of global agricultural water demand (~460 km^3 yr^{-1}) (chapter 3). This is more than a quarter of total surface water supply to irrigation. Reservoirs are therefore of major importance in irrigation water supply and food production. Although those reservoirs have increased the water availability for agriculture during the 20th century, they will not be able to support all further increases in irrigation demand until 2100. The irrigation water demand by the end of the 21st century will be 30% higher than around the year 2000 (chapter 4). This will mainly be the result of an expansion of irrigated areas in combination with yield increases that are necessary to produce the required food. According to the analysis described in chapter 4, roughly 25% of this irrigation water demand in 2100 cannot be supplied. The effects of climate change are likely to have large local impacts on water supply and demand, but will be of less importance at global scale. The water shortage will result in a reduction of annual global irrigated crop production around 20% or 400 Mton dry matter harvestable products. Crop losses will be mainly concentrated in South Asia and Southern Africa.

Different solutions are possible to reduce the water shortage. Adaptation, by improving irrigation efficiency and increasing the storage capacity of large reservoirs, can secure a larger part of the crop production. In chapter 5 this was shown for a selection of five river basins in South Asia. However, it was also shown that the best solution differs per basin and that more detailed analysis is required for the actual design of adaptation measures.

The results presented in this thesis provide an important step forward in the assessment of global water resources in relation to the agricultural system. The understanding of global hydrology was improved, first by making a validation of simulated river flow for many basins (chapter 2), and second by estimating the effect of irrigation withdrawals and reservoir operation on the global water cycle. Further, a quantification of the contribution of reservoirs to irrigation water supply at river basin, continental and global scale was made. Whereas some previous work is done on including the effect of large scale reservoirs on discharge (Haddeland et al., 2006b; Hanasaki et al., 2006), none of these studies quantified the increase in water resources available for agriculture as a result of reservoirs.

By using a model that represents both hydrology and crop growth it was possible to review land use and food production scenarios from a hydrological perspective and estimate impacts of water shortage on crop production. Finally, the modelling system was used for a quantitative assessment of the effect of two adaptation options: an increase in reservoir capacity and an overall improvement of irrigation efficiency. This is one of the first studies that quantifies the efficiency of different adaptation options, while previous studies on adaptation were mostly qualitative.

6.2 Synthesis

In the synthesis below different aspects of modeling global water resources for agriculture are discussed, illustrated by the results from this thesis. The discussion is divided in three categories: data, modeling concepts and future scenarios. Based on this discussion, an uncertainty assessment is made and recommendations for future research are identified. Final conclusions are presented in the last paragraph.

6.2.1 Data

6.2.1.1 Climate forcing

In chapter 2, it was shown that the uncertainty in precipitation input has a large effect on the simulated discharge, which complicates proper model validation or calibration. Comparison of seven global precipitation datasets at basin level showed an average precipitation uncertainty of 30%, which led to an even larger average uncertainty of discharge (90%). The large variation between the different gridded precipitation datasets was caused by both measurement errors at the gauges and introduced by the spatial interpolation of those observations to a grid. For each basin the minimum and maximum mean annual and mean seasonal precipitation was defined as the precipitation uncertainty, without further quality consideration.

However, part of the uncertainty might be reduced by accounting for known strengths and weaknesses of different datasets. Particularly at high latitudes and in regions with difficult topography, datasets that implemented corrections for snowfall undercatch and orography are better (Adam et al., 2006; Adam and Lettenmaier, 2003). The recently released Watch Forcing Data (WFD) (Weedon et al., 2011) provides an improvement over the datasets used in chapter 2. This dataset contains daily fields for precipitation that are cumulating to monthly totals of an improved version of the GPCC dataset. That dataset was adjusted for systematic bias caused by gauges undercatch (Weedon et al., 2011).

Chapter 2 showed the effect of only one climate input variable. Precipitation is regarded the most important input variable for a hydrological model, illustrated by the amount of studies that focus on the effect of precipitation inputs on discharge or runoff calculations (e.g. Fekete et al., 2004; Pavelsky and Smith, 2006; Voisin et al., 2008). However, uncertainty in other climate variables will also affect discharge simulations to a lesser known extent. Temperature influences evapotranspiration and hence, the resulting runoff, but there are no studies that quantify the effects of uncertainties in 20th century temperature on hydrological simulations. Uncertainty in discharge calculations caused by uncertain temperature input is expected to be lower than precipitation, because it is no direct input to the water balance. Moreover, uncertainties itself will also be smaller, as temperature is a variable that is easy to measure and easier to interpolate spatially than precipitation.

Potentially larger uncertainty is introduced by the radiation data (net longwave and shortwave downward radiation), although this gets little attention in the scientific literature. Haddeland et al. (2012) showed the sensitivity of evapotranspiration and runoff simulations to radiation input. Even if temperature and precipitation were already bias corrected using the Watch Forcing Data (Weedon et al., 2011), they showed that evapotranspiration simulated by LPJmL in the Nile and Ganges-Brahmaputra basins would have been significantly lower if radiation would also have been corrected. This suggests that the calculated irrigation water demand in chapter 4 for those regions would also be somewhat lower if climate input was used that was bias corrected for radiation. The effect of errors in radiation forcing data might have more impact on simulated irrigation water demand by LPJmL than previously assumed.

The uncertainty in 20th century datasets for radiation is however not easy to quantify, because there are little global datasets available for comparison. Given the scarce number of measurements for radiation, the uncertainty might be large but hard to correct.

6.2.1.2 Land use

Estimates of total global or continental irrigation water demand are to a large extent depending on the land use dataset used (Wisser et al., 2008). Land use datasets that include irrigated areas (e.g. Fader et al., 2010; Portmann et al., 2010; Siebert et al., 2005; Thenkabail et al., 2008) report total global irrigated areas between 215 (Fader et al., 2010) and 446 Mha (Thenkabail et al., 2008). The differences between those datasets are partly caused by different definitions of irrigated area, e.g. the ‘actually irrigated area’, that is lower than the ‘area equipped for irrigation’ and the ‘irrigated harvested area’, that accounts for cropping intensity. Wisser et al. (2008) forced a hydrological model with combinations of 2 different land use datasets and 2 climate datasets. This resulted in a range of estimates of global mean annual irrigation water demand from 2200 to 3800 km^3. The large spread was mainly attributed to the different datasets for irrigated areas.

The results in chapter 3 and 4 also show a difference in calculated irrigation water demands. Irrigation water demand in chapter 3 was estimated to be 2650 km^3 yr^{-1} (1981-2000) by using land use dataset of Fader et al. (2010) (215 Mha irrigated area) and the gridded climate dataset

CRU TS2.1 (Mitchell and Jones, 2005). In chapter 4, current global irrigation water demand was estimated to be much higher (3900 km^3 yr^{-1} for the same period) by using another land use dataset (corresponding to the 276 Mha irrigated area of the Global Map of Irrigated Areas (Siebert et al., 2005)) and other climate forcing (using bias corrected outputs of 3 GCMs (Hagemann et al., 2011)). Part of this difference can be explained by the use of different land use datasets, although it is also partly related to climate input, especially the biased radiation in these climate datasets (see previous section).

6.2.1.3 Irrigation water efficiency

The irrigation efficiency determines the difference between the plant water demand and the actual withdrawal. These efficiencies depend on both the irrigation system (e.g. surface vs. sprinkler or drip irrigation) and the conveyance system (open channels vs. pipeline conveyance). Efficiencies and are generally much higher in Western Europe and the USA than in countries like Pakistan, India and China (Rohwer et al., 2007). In this thesis efficiencies were applied at country level based on estimations by Rowher et al (2007). Net irrigation water requirements calculated by the crop module in LPJmL were multiplied with the efficiency factors to estimate the gross irrigation (withdrawal) demand. Therefore, the calculated irrigation water demand is to a large extent influenced by the applied irrigation efficiencies.

Assuming one irrigation efficiency factor per country is the appropriate level of detail for a global model. This however means that there is no accounting for within country differences in efficiencies caused by irrigation methods. This also indicates that calculated groundwater withdrawals might be overestimated, as groundwater irrigation is generally more efficient, due to less conveyance losses.

6.2.1.4 Validation data

Model performance and the effect of model improvements can only be tested if simulations can be validated with observed data of good quality and spatial coverage. Global water availability is usually validated with observed river discharge data collected by the Global Runoff Data Centre (GRDC, 2007) (as was done in chapter 2 and 3). However, many of the data records have only limited temporal coverage, only two third of the 300 stations used in chapter 2 had more than 5 years covered between 1979 and 1999. For India, there was no discharge data for the Farakka station (most downstream measuring station on the Ganges in India) after 1979, which made validation of river flows in chapter 5 difficult.

Simulated irrigation withdrawals can be compared with country statistics (FAO, 2012b), as e.g. done in Rost et al. (2008), and crop yields with national yield data reported to the Food and Agricultural Organisation (Fader et al., 2010; FAO, 2012a). The quality of those data sources is questionable. Irrigation water withdrawals and yields are typically measured at field scales, and difficult to aggregate to country level, as that requires dense monitoring. Moreover, the reported data might also be adjusted for political reasons.

6.2.2 Modeling concepts

LPJmL simulates water availability in rivers, lakes and reservoirs. It explicitly distinguishes extractions from those sources. Groundwater availability is not simulated explicitly, but is estimated by combining model results with available data on groundwater use for irrigation. Chapter 3 introduced the reservoir module of LPJmL and in chapter 4 the withdrawal from groundwater was added to the analysis. The used modeling concepts are mostly influencing the simulations of water availability and demand for agriculture and are discussed below.

6.2.2.1 Water availability from reservoirs

Both the extent of irrigated area and the amount of reservoirs showed a same steep increase during the 20th century, especially in the 1950s and 1960s (Chao et al., 2008; Freydank and Siebert, 2008). This correlation already suggests that reservoirs play an important role in irrigation water supply. Thirty percent of the large reservoirs are built primarily for irrigation (ICOLD, 2007). Although the effect of reservoirs on river flows was studied before (Haddeland et al., 2006b; Hanasaki et al., 2006), the study in chapter 2 provided the first quantitative estimates of the contribution of reservoirs to irrigation water supply and food production at global, continental and river basin scale. Therefore a reservoir operation scheme was implemented in LPJmL for all the geo-referenced dams in the recently developed GRanD database, which contains information of around 7000 global reservoirs with a cumulative capacity of 6000 km^3 (Lehner et al., 2011).

There are no data or other model results available on the contribution of large scale reservoirs to global and continental irrigation water supply. Therefore, the performance of the reservoir operation model could only be validated on discharge simulations. It was shown that the implementation of a reservoir operation scheme improved the simulations of discharge for most impacted rivers (chapter 3).

Both in chapter 3 and 4 it was estimated that reservoirs currently fulfil 17% of the total global irrigation water demand, and supply a quarter of all surface water used for irrigation. This is in line with coarse numbers provided by the World Commission on Dams. They state that 30-40% of the irrigated areas rely on water from reservoirs and that reservoirs contribute to 12-16% of the world food production (WCD, 2000).

In order to test the robustness of the simulated water supply from reservoirs, a sensitivity analysis was performed for the most important parameter choices (table 3.1). The estimated water supply from reservoirs was only to a small extent dependent on arbitrary model design choices that were unverifiable, like the distance of water transport from a reservoir, minimum release to the river and number of days that the water is stored in the conveyance system. Therefore, the results are believed to be robust at global scale.

The sensitivity analysis also showed that the most important factor for the estimation of water supply from reservoirs was the reservoir capacity. The results were more sensitive to changes in capacity than in model parameters (table 3.1). Therefore, it should be considered that implemented capacities could be overestimated.

In the simulations, some reservoirs were completely empty during part of the year due to large downstream irrigation water demand. In reality there is a part of storage capacity that is never used due to gravitational restrictions. This is called inactive storage. The usable capacity is therefore always lower than the reported capacity of a reservoir.

A second aspect affecting the usable capacity, which was not taken into account in the approach, is reservoir sedimentation. Every river transports a certain load of sediments which are, in case of a reservoir, partially trapped behind the dam and slowly filling up the reservoirs storage capacity (Vörösmarty et al., 2003). Therefore, the storage capacity of large dams is usually decreasing over time. The above considerations suggest that contribution of reservoirs to irrigation water supply might somewhat lower than the estimates in this thesis.

Developing globally applicable general operation rules for reservoirs is by definition a simplification, because any information on the operation of individual dams is not taken into account. This means that simulations using management information from individual dams regarding their outflow or irrigated area would give more accurate results locally.

All reservoirs that supply water for irrigation are operated according to the same rules, regardless of the size of the reservoir. An area supplied from a (relatively) small reservoir can be unrealistically large. At the same time, an irrigated area located in a region with many reservoirs can be supplied from up to 50 different reservoirs, which is also unrealistic.

Some reservoirs might be placed at the wrong location on the grid. The GRanD database which was used in this study (Lehner et al., 2011), provides coordinates for the outlets of 7000 of the largest reservoirs. For the implementation in LPJmL those dams were coupled to a location on a gridded river network (Vörösmarty et al., 2000b). Although locations for around 25 dams were corrected to fit the river system schematization, this manual check was only done for the 190 dams with a capacity larger than 5 km^3. There might be an amount of smaller reservoirs placed on the wrong river stretch, which might have consequences for the inflow and therefore the simulated water availability from this particular reservoir.

The application of global rules and the inevitable errors in dam locations will result in over- or underestimations of water supply from individual dams. However, it is believed that underestimations for one particular reservoir are compensated by overestimations elsewhere. Therefore, the model is suitable to estimate reservoir contributions to irrigation water supply and food production over large geographical domains.

6.2.2.2 Water availability from groundwater

Groundwater is estimated to contribute around 40% to global irrigation water supply (e.g. chapter 4, (Döll et al., 2012; Siebert et al., 2010)), but in some regions like India this contribution is much higher (chapter 5 and (Siebert et al., 2010)). It is also known that in some regions those withdrawals cause a depletion of groundwater, but recent quantifications of this depletion at global scale vary considerably between 27 and 283 km^3 per year (Konikow, 2011; Wada et al., 2010b). Because surface water alone cannot fulfill all irrigation water needs, it is important to account for groundwater availability in water resources assessments. Estimates of the volumes that can be withdrawn sustainably are essential, as well as knowledge about how long deep groundwater reserves can still be exploited.

As most global hydrological models, LPJmL does not have an explicit representation of groundwater reservoirs nor groundwater recharge. The soil is schematized as a column of two layers of 0.5 and 1 meter depth. Water infiltrates, runs off when it is above field capacity, transpires depending on vegetation and rooting depth and percolates to the deeper layer (Gerten et al., 2004). Water percolating through the second layer is directly added to runoff and routed through the system of rivers, lakes and reservoirs. Therefore, any groundwater recharge is directly added to surface water without time delay.

The irrigation demand calculated by LPJmL can be supplied from surface water (rivers, lakes and reservoirs, in that order of preference). If the surface water is (partly) unavailable, water can be supplied from an undefined external source (Rost et al., 2008).

Siebert et al. (2010) compiled a global dataset on shares of groundwater and surface water consumption of irrigation, that was based on an extensive collection of national and subnational data on areas equipped for groundwater irrigation and model calculations of irrigation requirements. In chapter 4, these data were combined with simulated irrigation water demands to estimate current groundwater withdrawals at basin level (method described in annex A). The irrigation water supplied from surface water as calculated by the model, was complemented with the estimated groundwater, and the remaining unfulfilled demand was assumed to be unavailable.

There are some inconsistencies in the chosen approach, which are the result of model design of LPJmL in combination with characteristics of the dataset by Siebert et al (2010) and lead to uncertainty in the estimate of groundwater withdrawals.

First, LPJmL does not simulate any groundwater recharge, but adds this directly to runoff. Therefore, shallow groundwater is included in the surface water availability of LPJmL, although it is underestimated due to the lacking time delay (Gerten et al., 2004; Rost et al., 2008, chapter 4). Siebert's data (2010) does not distinguish between shallow or deep groundwater and therefore the reported extractions of groundwater are including both the shallow and deep groundwater, sustainable and unsustainable extractions. In the analysis presented in chapter 4, none of the groundwater was extracted from the available surface water in LPJmL. Secondly, Siebert (2010) distinguished areas to be irrigated either from groundwater or from surface water. In the LPJmL modelling approach however, each irrigated field can be supplied from different sources at the same time: rivers and lakes, reservoirs and groundwater.

Finally, Siebert et al. (2010) do not provide information on the actual availability of the groundwater. In the analyses of chapter 4 it was assumed that the calculated groundwater withdrawal volumes based on Siebert's data were available, and that any demand that was not supplied from surface or groundwater, was unavailable.

Siebert et al. (2010) provide the only spatial explicit estimates of global groundwater use for irrigation that are based on a combination of observations and reports (on areas equipped for groundwater irrigation) and model results (on consumption on these irrigated areas). Despite the inconsistencies described above, it was therefore regarded an appropriate method to estimate current groundwater withdrawals. However, to better estimate future groundwater availability, quantitative data on remaining exploitable volumes are needed. Since many years the International Groundwater Resources Assessment Centre (IGRAC, www.un-igrac.org) collects information on groundwater aquifers, which is summarized in a map of transboundary aquifers of the world. This map shows only the extent, and not volume of groundwater aquifers and therefore cannot directly be used in simulations. The quantification of sustainable groundwater use is getting a lot of scientific attention, reflected in recent studies that estimate groundwater depletion (Wada et al., 2012) or net abstraction (Döll et al., 2012) at global scale. The first quantification of total groundwater storage was until now only done for Africa (MacDonald et al., 2012).

6.2.2.3 Effect of CO_2 concentration on irrigation water demand

Agricultural water demand does not only depend on irrigated area, climate and efficiency of irrigation systems, but also on the water use efficiency at crop level, i.e. the volume of water used per unit biomass production. This water use efficiency of crops increases with higher atmospheric CO_2 concentrations. However, the magnitude of the effect of CO_2 fertilization on crop production and therefore water use is still unclear. This is especially the case for CO_2 concentrations that are expected towards the end of the 21st century (Nakicenovic and Swart, 2000) which have not yet been simulated in laboratory and field experiments (Ewert et al., 2007; Long et al., 2006; Tubiello et al., 2007).

LPJmL incorporates the effect of CO_2 concentrations in its representation of potential canopy conductance and maximum net daytime photosynthesis (Gerten et al., 2007). Due to the absence of any representation of nutrient or other limitations in LPJmL, it simulates a rather strong effect of rising CO_2 concentrations on crop production increase, transpiration decrease and therefore irrigation water demand decrease.

In chapter 4, simulations of climate change effects on irrigation water demand and global crop production included the effect of rising CO_2 concentrations. The simulated crop production and irrigation water demand were compared with the same simulations using constant CO_2 concentrations (figure 4.1). The simulated effect of CO_2 fertilization was found to be especially large on rainfed crop production. To a lesser extent, the CO_2 effect compensated for the otherwise slightly negative effects of rising temperatures and precipitation changes on irrigated crop yields and irrigation water demand. Including or excluding the simulated CO_2 effect did not change the results of the study in chapter 4, i.e. the fraction of crop production at risk of water shortage. However, it does show that the assessments of climate change effects on future crop production and water demands in general are very sensitive to the representation of CO_2 fertilization.

6.2.2.4 Water demand related to cropping patterns

There are two issues related to the simulation of cropping patterns in LPJmL that could affect simulations of irrigation water demand. First, LPJmL does not use prescribe cropping patterns (e.g. from Portmann et al., 2010), but calculates sowing dates internally based on climate input and soil moisture (Waha et al., 2012). The advantage of these calculated sowing dates is that potential shifts in cropping calendar caused by climate change can be simulated by the model. The simulated sowing dates showed good agreement with observations (Waha et al., 2012). However, in some regions, the calculation of seasonal irrigation demand might be affected by small mismatches between the observed and simulated growing season.

Secondly, LPJmL does not simulate multiple cropping cycles (except for rice, see Bondeau et al., 2007), although this is common practice in many irrigated areas like India, China and west Africa (Portmann et al., 2010; Siebert et al.; Thenkabail et al., 2008). Consequently, irrigation demand in those areas might be underestimated, although not all crop rotations need equal amounts of water.

6.2.3 Future scenarios

Chapter 4 and 5 of this thesis project water resources and crop production based on climate and socio-economic scenarios for the future. The use of climate change and land use change scenarios introduces an additional source of uncertainty which is discussed here.

6.2.3.1 Climate change

Since it is unknown how population and the global economy will evolve, several alternative storylines that represent a range of potential futures of the socio-economic system were developed for IPCC-SRES (Nakicenovic and Swart, 2000). Based on the resulting emission scenarios, global climate models (GCMs) have projected global average temperature changes ranging between 1.1 and 6.4 degree Celsius until 2100, depending on the emission scenario and climate model used (IPCC, 2007).

Projected patterns of climate change vary substantially between GCMs, even when the same emission scenario is used. This is especially the case for precipitation. Climate models tend to agree about drying trends in the Mediterranean, Southern Africa and Australia and wetting trends in large parts of Canada, Scandinavia and Russia. Conflicting trends are simulated for e.g. Central Asia, India and China which are very important regions for the global (irrigated) food production (chapter 4 and 5).

In chapter 4, two scenarios were used to reflect the uncertainty about the future socio-economic system and climate. Those were the two most diverging scenarios of IPCC-SRES regarding population growth (relatively low in B1 vs. high in A2) and the development of the economy (globalisation in B1 vs. regionalisation in A2) and therefore relatively low (B1) and high (A2) greenhouse gas emissions. Both emission scenarios were simulated by 3 Global Circulation Models (GCMs) to reflect uncertainty in the climate system. This ensemble of forcing data, resulting from the combination of 2 emission scenarios with 3 GCMs led to a range of projections of future water availability (appendix figure A2).

In chapter 5, only one emission scenario was used to project climate change for the Indian subcontinent. Because the time horizon in this study was 2050 (it was 2100 in chapter 4), using one emission scenario was justified, as the greenhouse gas concentrations in the different emission scenarios only start to seriously diverge after 2050. Moreover, global climate models tend to disagree about the sign of precipitation change in this region (IPCC, 2007). This suggests that climate change uncertainty in this region is more related to uncertainty about complex processes that lead to (changes in) monsoon patterns and orographically induced precipitation than the emission scenario. Therefore, it is more important to use multiple climate models than multiple emission scenarios. Regional climate models (RCMs) are run at higher resolutions than GCMs, and are therefore better able to capture monsoon dynamics (Rupa Kumar et al., 2006) and climate patterns related to topography. Therefore an ensemble of 4 regional climate simulations was used in chapter 5: 2 GCM simulations downscaled by 2 Regional Climate Models (RCMs).

The RCM climate projections in chapter 5 and the GCM projections in chapter 4 showed uncertainty in projections of future precipitation (figure 5.3 and 5.4) which affected the resulting discharge calculations (figure A2). It was however found that in most regions, the effect of uncertainty in forcing data on simulated irrigation water demand and the surface water withdrawals was relatively small (figures 4.3b and 5.5).

6.2.3.2 Land use change

In chapter 4 and 5 land use projections developed within the WATCH project (www.eu-watch.org) were used. Those were similar to previous land use projections (Fischer et al., 2005). The land use scenarios relate to A2 and B1 storylines and were developed by combining the Global Agro Ecological Zones model (GAEZ) and the Basic Linked Systems Model (BLS). The Basic Linked Systems model consists of a collection of regional economic models that are simulating requirements, trade and production for a number of commodities (chapter 4, Fischer et al., 2005). Yield calculations are provided by GAEZ, a crop growth model that simulates actual and potential crop yields based on climate, soil and management information. The resulting land use projections contain fractions of rainfed and irrigated cropland at half degree gridcells for each decade until 2100, combined with region and crop specific projections of yield increases. The uncertainty in future water demand resulting from the uncertainty in land use change patterns is only accounted for by the consideration of 2 alternative development paths B1 and A2. To my knowledge, other land use scenarios for the SRES storylines that explicitly account for the increase in irrigated areas do not exist. The IMAGE model (MNP, 2006) projects future extent of agricultural area using a method similar to BLS-GAEZ, but do not (yet) account for irrigated area expansion.

Land use change is a complex process with many different driving forces. Population growth (Grubler et al., 2007), global commodity trade, dietary preferences (see e.g. Stehfest et al., 2009 for the effect of this on land use scenarios), technological change leading to yield improvements, climate change and biophysical conditions will all influence the future land use. Development of land use scenarios therefore requires a very interdisciplinary approach. Using a set of land use projections would certainly help identifying uncertainty related to the extent and location of irrigated area expansion.

An important aspect of the land use scenario used in this study is that water availability was not considered a limiting factor in its development. This makes (at least the irrigated part) of the land use scenarios unrealistic, because the projected yield increases might not be achieved. This means that production will have to be relocated to locations with abundant water or that more expansion is needed. Chapter 4 showed the impact of potential land use change on water scarcity, but the feedback from water availability on land use development was not accounted for.

6.2.4 Assessment of uncertainties

The main uncertainties related to modeling of water availability and demand for irrigated agriculture can be divided in three categories as discussed above: input data, modeling concepts and future scenarios.

Without additional studies, it is hard or even impossible to quantify the relative impact of these uncertainties on water resources assessments. The quantification of uncertainty related to input variables can be addressed by running a model with multiple inputs as was done in chapter 2, but an assessment of the effect of parameterizations of model processes can only be made by comparing different alternative parameterizations implemented in different models (e.g. Haddeland et al., 2011). Studies that use multiple models forced by multiple datasets would help identifying and quantifying the most important uncertainties in relation to water resources availability and demand (see next section). However, the relative importance of an uncertainty factor is depending on the focus of the study.

Table 6.1 gives an overview of the uncertainties affecting the results in this thesis and indicates whether they are mainly influencing the simulation of agricultural water availability or demand. With respect to the research question in this thesis, i.e. the assessment of water resources *related to food production* the results of this thesis suggest that further investigation should focus on the highlighted factors. This study (chapter 4) re-confirms (as before e.g. Vörösmarty et al., 2000c) that increasing water demand will be the most important factor leading to future water scarcity in agriculture. Therefore, there should be more focus on the uncertainty related to quantification of current and future irrigation water demand, mainly introduced by uncertainty regarding land use change scenarios and CO_2 effects. Further, as groundwater is such an important contributor to irrigation water supply, it is very important to improve estimates of available groundwater resources to sustain future agriculture. Because surface water alone will not be sufficient to supply all the water needed to sustain future irrigated agriculture, large volumes of groundwater supply will still be required (chapter 4), even when the surface water storage will be increased or irrigation efficiency is drastically improved (chapter 5).

Given all uncertainties related to the quantification of agricultural water availability and

Table 6.1 Main uncertainties affecting calculations of water availability and demand for irrigated agriculture

Category	Factor	mainly affecting
Data	Precipitation	availability
	Radiation	demand
	irrigated area extent	demand
	irrigation efficiency	demand
Model	supply from reservoirs	availability
	groundwater supply	availability
	CO_2 effect	demand
	Cropping pattern	demand
Scenarios	climate change	availability
	land use change	demand

demand, the main conclusions of this thesis are still valid. Although the effect of uncertainty in precipitation on simulated discharge is large (chapter 2), this seems to be less the case for irrigation water demand and withdrawal (chapter 4 and 5). The contribution of reservoirs to irrigation water supply is found to be robust when using different land use and climate input (16-17% in chapter 3 and 4).

Although there is uncertainty about the exact extent of future irrigated areas and hence, irrigation water demand, there is consensus about the expected population increase and the need for irrigated areas to expand to feed this population (FAO, 2006; Molden, 2007). Therefore irrigation demand will increase.

For the most important uncertainties that would affect the main results of this thesis, the most optimistic variant was implemented: beneficial CO_2 effects can be less but not more than simulated in chapter 4, groundwater supply can be lower than the assumed equal-to-today volumes, and other users can use part the water that was now allocated to agriculture in the simulations.

Although the exact quantitative effect of adaptation is uncertain, a spatial analysis on the effects of adaptation as performed in chapter 5 can help identifying where water scarcity will be most profound and where adaptation would be most beneficial.

6.2.5 Recommendations for future research and final conclusions

6.2.5.1 Multi-data multi model-approach

It is evident that reduced uncertainty in datasets of current and future climate would improve the accuracy of water resources assessments, as would an improved representation of processes in the model. However, limited resources ask for prioritization of research needs. Multi-data and multi-model studies of global water resources can help prioritizing research, and are informative for a number of reasons. First, they can be used to identify and quantify uncertainties and their relative impact on the simulation of water resources. Further, those multi data multi model approaches can also reduce uncertainty and increase confidence in results. If several model simulations show the same trends and dynamics, this is an indication that results are robust.

Multi model assessment and intercomparisons can also be used as a benchmark for single models. Comparing results for different variables and regions identifies which model processes are in line with, or much different from other models and would therefore need further investigation or improvement.

Although multi model approaches are very common in climate change modeling (as for example shown by the suite of models in the CMIP experiments for the IPCC (IPCC,2007), the first multi model approaches with impact models have just been finished, e.g. WaterMIP on water resources models (www.eu-watch.org/watermip). Others are still ongoing, like AgMIP on agricultural models (www.agmip.org) and ISI MIP on global impact models focussing on different sectors.

Based on the uncertainty analysis above, studies aiming at improving the understanding of water resources in relation to current and future agriculture should mainly focus on improved understanding of limitations in groundwater availability, future land use scenarios and the effect of elevated CO_2 concentrations on on crop yields and irrigation water demand.

6.2.5.2 Improved representation of variability and extremes

All assessments in this thesis have focused on mean annual results; the uncertainty in precipitation and resulting simulated discharge, the simulation of water supply from reservoirs, the crop yield reductions and also the impact of adaptation on the water availability, demand and food production in India were all averaged over a 20 year period. None of the studies considered any current variability or a potential increased variability due to climate change. However, considering that many climate models suggest an increase in extreme events in the future and that stability is an important aspect of food security (Godfray et al., 2010), further research on water resources related to food production could focus on the impact of extremes and changes in climate variability on water availability, water demand and resulting crop production.

6.2.5.3 Inter sectoral analysis of water resources

Although agriculture is the most important water user at global scale, other users should not be neglected. There are regions where those other users need larger shares than the global average and where conflicts between different sectors can arise. Therefore, global water resources assessments need to incorporate water requirements from those other users. Domestic and industrial water withdrawals were included in some previous water resources assessments, to estimate total aggregated water stress (Alcamo et al., 2007; Hanasaki et al., 2008b) or to limit water extractions for irrigation (Rost et al., 2008). Others have estimated in-stream requirements, e.g. for aquatic ecosystems (environmental flow) (Smakhtin et al., 2004) or hydropower production. However, trade-offs between different users, in terms of sector specific impacts have not been addressed so far and will be a challenging task.

6.2.5.4 Integrating water availability in food security studies

The direct effect of climate change on future food production, and hence food security, is the subject of many studies (Brown and Funk, 2008; Fischer et al., 2005; Muller et al., 2011; Parry et al., 2004; Schmidhuber and Tubiello, 2007), and taken into account in assessment on the future of agriculture (Fischer et al., 2005; Strengers et al., 2004). However, as irrigated agriculture is such an important contributor to global food supply, it is strange to realize that those food system studies exclude the effect associated with changes in freshwater availability and demand for irrigation. Irrigation water is assumed to remain available, even if irrigated areas will expand. Even in the on-going agricultural model intercomparison project, that aims at an 'improved characterization of risk of hunger and world food security' (www.agmip.org) does not account for risks related to limited freshwater availability.

On the other hand, global water resources studies project since years that water stress is likely to increase, caused by socio-economic and climate change (Alcamo et al., 2007; Arnell, 2004; Vörösmarty et al., 2000c), but they did not quantify impacts of this stress on the agricultural sector.

There is a need for these two research communities to start cooperating. The results in this thesis (mainly chapter 4) stress the need to further investigate the effects of (irrigation) water limitations on future food production. Therefore, hydrological constraints should be considered in agricultural assessments in order to develop land use change scenarios that are consistent with water availability. This will improve the assessment and the future planning of water resources management and food production. Further, it will improve the assessment of regions where adaptation will be inevitable to achieve of the required food production.

An important step forward is the coupling of LPJmL to the integrated assessment model IMAGE (MNP, 2006), which is currently being implemented. This coupling will result in improved land use scenarios, because the effect of limited water availability on crop production will be fed back into the land allocation model. Once completely implemented, including the allocation of new irrigated agriculture, this integrated model will be very suitable to study interactions between water and food production, as well as trade-offs with e.g. nature or biofuel production. A first analysis could test the hypothesis that water scarcity in irrigated agriculture will lead to more land expansion and therefore increasing pressure on natural ecosystems and biodiversity. This analysis could be done by isolating the effect of water availability on land use allocation in IMAGE, by first assuming that all irrigation water is available and comparing that with simulations in which water for irrigation is limited. This water limitation will probably show that further expansion of rainfed and (sub-optimally) irrigated areas is needed to compensate for the water related crop losses. Agriculture will therefore probably need to take more additional land than according to the current estimates (e.g. the 120 Mha additional land needed towards 2050 as projected by FAO (2006)). This will create extra pressure on ecosystems and biodiversity.

In a next step, it would be very interesting to assess the potential effect of large scale adaptation (like in chapter 5) on the land and water requirements for agriculture.

6.2.5.5 Final conclusions

Is there enough water to feed the population in 2100? Not if nothing is done, as shown by the analyses presented in this thesis. LPJmL has proven to be capable of simulating water fluxes at basin level (chapter 2). It now includes a representation of the operation of large reservoirs, which has improved the calculation of water availability for agriculture. Reservoirs were found to make a substantial contribution (~17%) to global irrigation water supply, and therefore food production (chapter 3). It was shown that the current projections of the future food system are not 'waterproof', and that the agricultural system represented in those projections might fail to produce ~8% of the needed food crop production due to irrigation water shortage (chapter 4). To fulfill all future water demands there is a clear need for adapting our water management systems. Improved irrigation efficiency and increased storage capacity in large reservoirs can help to reduce water scarcity and improve food production (chapter 5).

References

Adam, J.C., E.A. Clark, D.P. Lettenmaier, and E.F. Wood, 2006: Correction of global precipitation products for orographic effects. *Journal of Climate*, **19,** 15-38.

Adam, J.C., I. Haddeland, F. Su, and D.P. Lettenmaier, 2007: Simulation of reservoir influences on annual and seasonal streamflow changes for the Lena, Yenisei, and Ob' rivers. *Journal of Geophysical Research-Atmospheres*, **112**.

Adam, J.C., and D.P. Lettenmaier, 2003: Adjustment of global gridded precipitation for systematic bias. *Journal of Geophysical Research-Atmospheres*, **108,** 4257.

ADB, 2011: Asian Development Outlook, Asian Development Bank.

Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, C. S., D. Bolvin, A. Gruber, J. Susskind, J. Arking, and E. Nelkin, 2003: The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). *Journal of Hydrometeorology*, **4,** 1147-1167.

Aggarwal, P.K., P.K. Joshi, J.S.I. Ingram, and R.K. Gupta, 2004: Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. *Environmental Science & Policy*, **7,** 487-498.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rosch, and S. Siebert, 2003a: Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **48,** 317-337.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rosch, and S. Siebert, 2003b: Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **48,** 339-348.

Alcamo, J., M. Flörke, and M. Marker, 2007: Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **52,** 247-275.

Alcamo, J., and T. Henrichs, 2002: Critical regions: A model-based estimation of world water resources sensitive to global changes. *Aquatic Sciences*, **64,** 352-362.

Amarasinghe, U., T. Shah, H. Turral, and B.K. Anand, 2007: India's water future to 2025-2050: Business-as-usual scenario and deviations, IWMI, 47 pp.

Arnell, N.W., 1999a: Climate change and global water resources. *Global Environmental Change-Human and Policy Dimensions*, **9,** S31-S49.

Arnell, N.W., 1999b: A simple water balance model for the simulation of streamflow over a large geographic domain. *Journal of Hydrology*, **217,** 314-335.

Arnell, N.W., 2003: Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. *Hydrology and Earth System Sciences*, **7,** 619-641.

Arnell, N.W., 2004: Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change-Human and Policy Dimensions*, **14,** 31-52.

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier, 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, **438,** 303-309.

Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof, Eds., 2008: *Climate Change and Water*. IPCC Secretariat, 210 pp.

Beck, C., J. Grieser, and B. Rudolf, 2005: A New Monthly Precipitation Climatology for the Global Land Areas for the Period 1951 to 2000, German Weather Service, 181-190 pp.

Berezovskaya, S., D.Q. Yang, and D.L. Kane, 2004: Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds. *Geophysical Research Letters*, **31,** -.

Bergstrom, S., B. Carlsson, M. Gardelin, G. Lindstrom, A. Pettersson, and M. Rummukainen, 2001: Climate change impacts on runoff in Sweden - assessments by global climate models, dynamical downscaling and hydrological modelling. *Climate Research*, **16,** 101-112.

Bhadwal, S., H. Biemans, S. Nair, S. Balakrishnan, S. Ghosh, S. Das, S. Bhattachrya, and P. Gangopadhyay, submitted: Socioeconomic dynamics in a changing climate: development of global and local socioeconomic scenarios for India *Sci Total Environ*.

Biemans, H., T. Bresser, H. Van Schaik, and P. Kabat, 2006: Water and Climate Risks: A Plea for Climate Proofing of Water Development Strategies and Measures, Co-operative Programme on Water and Climate.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R.W.A. Hutjes, J. Heinke, W. von Bloh, and D. Gerten, 2011: Impact of reservoirs on river discharge and irrigation water supply during the 20th century. *Water Resources Research*, **47**.

Biemans, H., R.W.A. Hutjes, P. Kabat, B.J. Strengers, D. Gerten, and S. Rost, 2009: Effects of precipitation uncertainty on discharge calculations for main river basins. *Journal of Hydrometeorology*, **10,** 1011–1025.

Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, and D. Gerten, 2007: Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, **13,** 679-706.

Brown, M.E., and C.C. Funk, 2008: Climate - Food security under climate change. *Science*, **319,** 580-581.

Bruinsma, J., 2003: World Agriculture: Towards 2015/2030. An FAO Perspective.

Chao, B.F., Y.H. Wu, and Y.S. Li, 2008: Impact of Artificial Reservoir Water Impoundment on Global Sea Level. *Science*, **320,** 212-214.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton, 2007: Regional Climate Projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* S. Solomon, and Coauthors, Eds., Cambridge University Press.

Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettenmaier, and R.N. Palmer, 2004: The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic Change*, **62,** 337-363.

Cox, P.M., R.A. Betts, C.B. Bunton, R.L.H. Essery, P.R. Rowntree, and J. Smith, 1999: The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Climate Dynamics*, **15,** 183-203.

CPC, 2008: CPC Merged Analysis of Precipitation (CMAP). Climate Prediction Center.

CSD, 1997: Comprehensive Assessment of the Freshwater Resources of the World. Report of the Secretary General, United Nations Economic and Social Council.

de Fraiture, C., 2007: Integrated water and food analysis at the global and basin level. An application of WATERSIM. *Water Resources Management*, **21,** 185-198.

Döll, P., 2002: Impact of climate change and variability on irrigation requirements: A global perspective. *Climatic Change*, **54,** 269-293.

Döll, P., and K. Fiedler, 2008: Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences*, **12,** 863-885.

Döll, P., K. Fiedler, and J. Zhang, 2009: Global-scale analysis of river flow alterations due to water withdrawals and reservoirs. *Hydrology and Earth System Sciences*, **13,** 2413-2432.

Döll, P., H. Hoffmann-Dobrev, F.T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg, and B.R. Scanlon, 2012: Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*.

Döll, P., F. Kaspar, and B. Lehner, 2003: A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology*, **270,** 105-134.

Döll, P., and B. Lehner, 2002: Validation of a new global 30-min drainage direction map. *Journal of Hydrology*, **258,** 214-231.

Döll, P., and S. Siebert, 2002: Global modeling of irrigation water requirements. *Water Resources Research*, **38,** -.

Eickhout, B., H. Van Meijl, and A. Tabeau, 2006: Modelling agricultural trade an food production under different trade policies. *Integrated modelling of global environmental change. An overview of IMAGE 2.4*, A. F. Bouwman, T. Kram, and K. Klein Goldewijk, Eds., Netherlands Environmental Assessment Agency (MNP).

Elimelech, M., and W.A. Phillip, 2011: The Future of Seawater Desalination: Energy, Technology, and the Environment. *Science*, **333,** 712-717.

Ewert, F., J.R. Porter, and M.D.A. Rounsevell, 2007: Crop Models, CO2, and Climate Change. *Science*, **315,** 459-460.

Fader, M., S. Rost, C. Müller, A. Bondeau, and D. Gerten, 2010: Virtual water content of temperate cereals and maize: Present and potential future patterns. *Journal of Hydrology*, **384,** 218-231.

Falkenmark, M., J. Rockstrom, and L. Karlberg, 2009: Present and future water requirements for feeding humanity. *Food Secur*, **1,** 59-69.

FAO, 2006: World agriculture towards 2030/2050. Interim report.

FAO, 2011: *The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk.*

FAO, 2012a: http://faostat.fao.org/

FAO, 2012b: http://www.fao.org/nr/water/aquastat/main/index.

Fekete, B.M., C.J. Vörösmarty, and W. Grabs, 2000: Composite Runoff Fields Based on Observed River Discharge and Simulated Water Balances, Complex Systems Research Center, University of New Hampshire, USA.

Fekete, B.M., C.J. Vörösmarty, and W. Grabs, 2002: High-resolution fields of global runoff combining observed river discharge and simulated water balances. *Global Biogeochemical Cycles*, **16,** 1042.

Fekete, B.M., C.J. Vörösmarty, J.O. Roads, and C.J. Willmott, 2004: Uncertainties in precipitation and their impacts on runoff estimates. *Journal of Climate*, **17,** 294-304.

Fischer, G., M. Shah, F.N. Tubiello, and H. van Velhuizen, 2005: Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990-2080. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **360,** 2067-2083.

Fischer, G., M. Shah, and H. Van Velthuizen, 2002: Climate Change and Agricultural Vulnerability, International Institute for Applied Systems Analysis.

Fischer, G., F.N. Tubiello, H. van Velthuizen, and D.A. Wiberg, 2007: Climate change impacts on irrigation water requirements: Effects of mitigation, 1990-2080. *Technological Forecasting and Social Change*, **74,** 1083-1107.

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, and P.K. Snyder, 2005: Global consequences of land use. *Science*, **309,** 570-574.

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockstrom, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks, 2011: Solutions for a cultivated planet. *Nature*, **478,** 337-342.

Foster, S.S.D., and P.J. Chilton, 2003: Groundwater: the processes and global significance of aquifer degradation. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, **358,** 1957-1972.

Freydank, K., and S. Siebert, 2008: Towards mapping the extent of irrigation in the last century: time series of irrigated area per country, Institute of Physical Geography, University of Frankfurt.

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha, 2011: Global water availability and requirements for future food production. *Journal of Hydrometeorology*.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008: Causes of change in 20th century global river discharge. *Geophysical Research Letters*, **35,** -.

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch, 2004: Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology*, **286,** 249-270.

Gerten, D., S. Schaphoff, and W. Lucht, 2007: Potential future changes in water limitations of the terrestrial biosphere. *Climatic Change*, **80,** 277-299.

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas, and C. Toulmin, 2010: Food Security: The Challenge of Feeding 9 Billion People. *Science*, **327,** 812-818.

GOI, 2007: Elevent Five Year Plan 2007-2012. Volume III: Agriculture, Rural Development, Industry, Services and Physical Infrastructure. G. o. I. P. Commision, Ed., Oxford University Press.

Gordon, C., C. Cooper, C.A. Senior, H. Banks, J.M. Gregory, T.C. Johns, J.F.B. Mitchell, and R.A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*, **16,** 147-168.

Graf, W.L., 1999: Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research*, **35,** 1305-1311.

Graf, W.L., 2006: Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, **79,** 336-360.

GRDC, 2007, GRDC in the Bundesanstalt fuer Gewaesserkunde, 56068 Koblenz, Germany, http://grdc.bafg.de.

Grubler, A., B. O'Neill, K. Riahi, V. Chirkov, A. Goujon, P. Kolp, I. Prommer, S. Scherbov, and E. Slentoe, 2007: Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. *Technological Forecasting and Social Change*, **74,** 980-1029.

Grumbine, R.E., and J.C. Xu, 2011: Mekong Hydropower Development. *Science*, **332,** 178-179.

Gupta, S.K., and R.D. Deshpande, 2004: Water for India in 2050: first-order assessment of available options. *Current Science*, **86,** 1216-1224.

Haddeland, I., D.B. Clark, W. Franssen, F. Ludwig, F. Voß, N.W. Arnell, N. Bertrand, M. Best, S. Folwell, D. Gerten, S. Gomes, S.N. Gosling, S. Hagemann, N. Hanasaki, R. Harding, J. Heinke, P. Kabat, S. Koirala, T. Oki, J. Polcher, T. Stacke, P. Viterbo, G.P. Weedon, and P. Yeh, 2011: Multi-Model Estimate of the Global Terrestrial Water Balance: Setup and First Results. *Journal of Hydrometeorology*.

Haddeland, I., J. Heinke, F. Voss, S. Eisner, C. Chen, S. Hagemann, and F. Ludwig, 2012: Effects of climate model radiation, humidity and wind estimates on hydrological simulations. *Hydrology and Earth System Sciences*, **16,** 305-318.

Haddeland, I., D.P. Lettenmaier, and T. Skaugen, 2006a: Effects of irrigation on the water and energy balances of the Colorado and Mekong river basins. *Journal of Hydrology*, **324,** 210-223.

Haddeland, I., T. Skaugen, and D.P. Lettenmaier, 2006b: Anthropogenic impacts on continental surface water fluxes. *Geophysical Research Letters*, **33,** -.

Haddeland, I., T. Skaugen, and D.P. Lettenmaier, 2007: Hydrologic effects of land and water management in North America and Asia: 1700-1992. *Hydrology and Earth System Sciences*, **11,** 1035-1045.

Hagemann, S., C. Chen, J.O. Haerter, J. Heinke, D. Gerten, and C. Piani, 2011: Impact of a Statistical Bias Correction on the Projected Hydrological Changes Obtained from Three GCMs and Two Hydrology Models. *Journal of Hydrometeorology*, **12,** 556-578.

Hanasaki, N., S. Kanae, and T. Oki, 2006: A reservoir operation scheme for global river routing models. *Journal of Hydrology*, **327,** 22-41.

Hanasaki, N., S. Kanae, T. Oki, K. Masuda, K. Motoya, N. Shirakawa, Y. Shen, and K. Tanaka, 2008a: An integrated model for the assessment of global water resources Part 1: Model description and input meteorological forcing. *Hydrology and Earth System Sciences*, **12,** 1007-1025.

Hanasaki, N., S. Kanae, T. Oki, K. Masuda, K. Motoya, N. Shirakawa, Y. Shen, and K. Tanaka, 2008b: An integrated model for the assessment of global water resources Part 2: Applications and assessments. *Hydrology and Earth System Sciences*, **12,** 1027-1037.

Huffman, G.J., R.F. Adler, P. Arkin, A. Chang, R. Ferraro, A. Gruber, J. Janowiak, A. McNab, B. Rudolf, and U. Schneider, 1997: The Global Precipitation Climatology Project (GPCP) Combined Precipitation Dataset. *Bulletin of the American Meteorological Society*, **78,** 5-20.

ICOLD, 2007: *World Register of Dams.* International Commission on Large Dams.

IMAGE-team, 2001: The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive Analysis of Emissions, Climate Change and Impacts in the 21st Century. RIVM, Ed.

Immerzeel, W.W., L.P.H. van Beek, and M.F.P. Bierkens, 2010: Climate Change Will Affect the Asian Water Towers. *Science*, **328,** 1382-1385.

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, 996 pp.

Jacob, D., 2001: A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. *Meteorol Atmos Phys*, **77,** 61-73.

Jacob, D., 2009: Regional Climate Models: Linking Global Climate Change to Local Impacts. *The Springer Encyclopedia of Complexity and Systems Science*, pp 7591-7602.

Kabat, P., M. Claussen, P.A. Dirmeyer, J.H.C. Gash, L.B. de Guenni, M. Meybeck, R.A. Pielke, C.J. Vörösmarty, R.W.A. Hutjes, and S. Lütkemeier, 2004: *Vegetation, water, humans and the climate : a new perspective on an interactive system.* Springer, XXIII, 566 pp.

Kavetski, D., S.W. Franks, and G. Kuczera, 2002: Confronting Input Uncertainty in Environmental Modelling. *Calibration of Watershed Models*, Q. Duan, H. V. Gupta, S. Sorooshian, A. N. Rousseau, and R. Turcotte, Eds., 49-68.

Kavetski, D., G. Kuczera, and S.W. Franks, 2006a: Bayesian analysis of input uncertainty in hydrological modeling: 1. Theory. *Water Resources Research*, **42,** W03407.

Kavetski, D., G. Kuczera, and S.W. Franks, 2006b: Bayesian analysis of input uncertainty in hydrological modeling: 2. Application. *Water Resources Research*, **42,** W03408.

Klein Goldewijk, K., and G. van Drecht, 2006: HYDE 3: Current and historical population and land cover. *Integrated modelling of global environmental change. An overview of IMAGE 2.4*, A. F. Bouwman, T. Kram, and K. Klein Goldewijk, Eds., Netherlands Environmental Assessment Agency.

Konikow, L.F., 2011: Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophys. Res. Lett.*, **38,** L17401.

Konzmann, M., D. Gerten, and J. Heinke, in revision: Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrological Sciences Journal*.

Kumar, K.K., K.R. Kumar, R.G. Ashrit, N.R. Deshpande, and J.W. Hansen, 2004: Climate impacts on Indian agriculture. *International Journal of Climatology*, **24,** 1375-1393.

Kumar, R., R.D. Singh, and K.D. Sharma, 2005: Water resources of India. *Current Science*, **89,** 18.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen, and I.A. Shiklomanov, 2007: Freshwater resources and their management. . *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. v. d. Linden, and C. E. Hanson, Eds., Cambridge University Press, 173-210.

Ladson, A.R., and L.J. White, 1999: An index of stream condition: Reference Manual, Department of Natural Resources and Environment.

Legates, D.R., 1987: A climatology of global precipitation. *Pub. Climatol.*, **40,** 1-85.

Legates, D.R., and C.J. Willmott, 1990: Mean Seasonal and Spatial Variability in Gauge-Corrected, Global Precipitation. *International Journal of Climatology*, **10,** 111-127.

Lehner, B., and P. Döll, 2004: Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology*, **296,** 1-22.

Lehner, B., C.A. Reidy Liermann, C. Revenga, B. Fekete, C. Vörösmarty, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J. Robertson, R. Rödel, N. Sindorf, and D. Wisser, 2011: High resolution mapping of global reservoirs and dams and their impact on downstream rivers. *Frontiers in Ecology and the Environment*.

Long, S.P., E.A. Ainsworth, A.D.B. Leakey, J. Nösberger, and D.R. Ort, 2006: Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations. *Science*, **312,** 1918-1921.

Lucas-Picher, P., J.H. Christensen, F. Saeed, P. Kumar, S. Asharaf, B. Ahrens, A. Wiltshire, D. Jacob, and S. Hagemann, 2011: Can regional climate models represent the Indian monsoon? . *Journal of Hydrometeorology*.

Ludwig, F., P. Kabat, S. Hagemann, and M. Dorlandt, 2009: Impacts of climate variability and change on development and water security in Sub-Saharan Africa. *Climate Change: Global Risks, Challenges and Decisions*, Copenhagen, Denmark, 10-12 March, 2009, S 29.02.

MacDonald, A., H. Bonsor, B.É.Ó. Dochartaigh, and R. Taylor, 2012: Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, **7,** 024009.

Marchant, R., and G. Hehir, 2002: The use of AUSRIVAS predictive models to assess the response of lotic macroinvertebrates to dams in south-east Australia. *Freshwater Biology*, **47,** 1033-1050.

Matsuura, K., and C.J. Willmott, 2007: Terrestrial Precipitation: 1900-2006 Gridded Monthly Time Series (version 1.01). Center for Climatic Research, Department of Geography, University of Delaware, Newark

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.C. Zhao, 2007: Global Climate Change Projections. *Climate Change 2007: The Physical Science Basins, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, and Coauthors, Eds., Cambridge University Press.

Milly, P.C.D., K.A. Dunne, and A.V. Vecchia, 2005: Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, **438,** 347-350.

Mitchell, T.D., and P.D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology*, **25,** 693-712.

MNP, 2006: *Integrated modelling of global environmental change. An overview of IMAGE 2.4.* Netherlands Environmental Assessment Agency (MNP).

Molden, D., Ed., 2007: *Water for Food Water for Life*. Earthscan.

Molden, D., U. Amarasinghe, M. Bhattarai, J. Wang, and I. Makin, 2002: Water and Food Security: Background paper for the World water development report.

Monfreda, C., N. Ramankutty, and J.A. Foley, 2008: Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, **22,** -.

Moors, E.J., A. Groot, H. Biemans, C.T. van Scheltinga, C. Siderius, M. Stoffel, C. Huggel, A. Wiltshire, C. Mathison, J. Ridley, D. Jacob, P. Kumar, S. Bhadwal, A. Gosain, and D.N. Collins, 2011: Adaptation to changing water resources in the Ganges basin, northern India. *Environmental Science & Policy*.

Muller, C., W. Cramer, W.L. Hare, and H. Lotze-Campen, 2011: Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108,** 4313-4315.

Nakicenovic, N., and R. Swart, Eds., 2000: *Special Report on Emission Scenarios*. Cambridge University Press.

New, M., M. Hulme, and P. Jones, 1999: Representing twentieth-century space-time climate variability. Part I: Development of a 1961-90 mean monthly terrestrial climatology. *Journal of Climate*, **12,** 829-856.

New, M., M. Hulme, and P. Jones, 2000: Representing twentieth-century space-time climate variability. Part II: Development of 1901-96 monthly grids of terrestrial surface climate. *Journal of Climate*, **13,** 2217-2238.

Nijssen, B., G.M. O'Donnell, D.P. Lettenmaier, D. Lohmann, and E.F. Wood, 2001: Predicting the discharge of global rivers. *Journal of Climate*, **14,** 3307-3323.

Nilsson, C., C.A. Reidy, M. Dynesius, and C. Revenga, 2005: Fragmentation and flow regulation of the world's large river systems. *Science*, **308,** 405-408.

OECD, 2008: *OECD Environmental Outlook to 2030.*

Oki, T., Y. Agata, S. Kanae, T. Saruhashi, and K. Musiake, 2003: Global water resources assessment under climatic change in 2050 using TRIP. *Water Resources Systems - Water availability and global change*, Sapporo.

Oki, T., Y. Agata, S. Kanae, T. Saruhashi, D. Yang, and K. Musiake, 2001: Global assessment of current water resources using total runoff integrating pathways. *Hydrological Sciences Journal*, **46,** 983-995.

Oki, T., and S. Kanae, 2006: Global hydrological cycles and world water resources. *Science*, **313,** 1068-1072.

Österle, H., F.W. Gerstengarbe, and P.C. Werner, 2003: Homogenisierung und Aktualisierung des Klimadatensatzes des Climate Research Unit der Universität of East Anglia, Norwich., Deutsche Klimatagung.

Parry, M.L., C. Rosenzweig, A. Iglesias, M. Livermore, and G. Fischer, 2004: Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change-Human and Policy Dimensions*, **14,** 53-67.

Parthasarathy, B., A.A. Munot, and D.R. Kothawale, 1988: Regression-Model for Estimation of Indian Foodgrain Production from Summer Monsoon Rainfall. *Agricultural and Forest Meteorology*, **42,** 167-182.

Pavelsky, T.M., and L.C. Smith, 2006: Intercomparison of four global precipitation data sets and their correlation with increased Eurasian river discharge to the Arctic Ocean. *Journal of Geophysical Research-Atmospheres*, **111,** -.

Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier, 2004: Mitigating the effects of climate change on the water resources of the Columbia River Basin. *Climatic Change*, **62,** 233-256.

Piani, C., G.P. Weedon, M. Best, S.M. Gomes, P. Viterbo, S. Hagemann, and J.O. Haerter, 2010: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. *Journal of Hydrology*, **395,** 199-215.

Poff, N.L., J.D. Olden, D.M. Merritt, and D.M. Pepin, 2007: Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America*, **104,** 5732-5737.

Pope, V.D., M.L. Gallani, P.R. Rowntree, and R.A. Stratton, 2000: The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3. *Climate Dynamics*, **16,** 123-146.

Portmann, F.T., S. Siebert, and P. Doll, 2010: MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, **24,** -.

Qiu, J., 2010: China faces up to groundwater crisis. *Nature*, **466,** 308-308.

Ramankutty, N., A.T. Evan, C. Monfreda, and J.A. Foley, 2008a: Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles*, **22,** GB1003.

Ramankutty, N., A.T. Evan, C. Monfreda, and J.A. Foley, 2008b: Farming the planet: Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles*, **22**.

Rockstrom, J., W. Steffen, K. Noone, A. Persson, F.S. Chapin, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley, 2009: A safe operating space for humanity. *Nature*, **461,** 472-475.

Rodell, M., I. Velicogna, and J.S. Famiglietti, 2009: Satellite-based estimates of groundwater depletion in India. *Nature*, **460,** 999-U980.

Roeckner, E., R. Brokopf, M. Esch, M. Giorgetta, S. Hagemann, L. Kornblueh, E. Manzini, U. Schlese, and U. Schulzweida, 2006: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. *Journal of Climate*, **19,** 3771-3791.

Rohwer, J., D. Gerten, and W. Lucht, 2007: Development of Functional Irrigation Types for Improved Global Crop ModellingNo. 104, Potsdam Institute for Climate Impact Research.

Rosegrant, M.W., X. Cai, and S.A. Cline, 2002: World water and food to 2025: Dealing with Scarcity, International Food Policy Research Institute.

Rosenberg, D.M., P. McCully, and C.M. Pringle, 2000: Global-scale environmental effects of hydrological alterations: Introduction. *Bioscience*, **50,** 746-751.

Rost, S., D. Gerten, A. Bondeau, W. Lucht, J. Rohwer, and S. Schaphoff, 2008: Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research*, **44**.

Rost, S., D. Gerten, H. Hoff, W. Lucht, M. Falkenmark, and J. Rockstrom, 2009: Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letters*, 044002.

Rupa Kumar, K., A.K. Sahai, K. Krishna Kumar, S.K. Patwardhan, P.K. Mishra, J.V. Revandekar, K. Kamala, and G.B. Pant, 2006: high-resolution climate change scenarios for India for the 21st century. *Current Science*, **90,** 334-345.

Schmidhuber, J., and F.N. Tubiello, 2007: Global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104,** 19703-19708.

Siebert, S., J. Burke, J.M. Faures, K. Frenken, J. Hoogeveen, P. Doll, and F.T. Portmann, 2010a: Groundwater use for irrigation - a global inventory. *Hydrology and Earth System Sciences*, **14,** 1863-1880.

Siebert, S., and P. Döll, 2010: Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology*, **In Press, Corrected Proof**.

Siebert, S., P. Döll, J. Hoogeveen, J.M. Faures, K. Frenken, and S. Feick, 2005: Development and validation of the global map of irrigation areas. *Hydrology and Earth System Sciences*, **9,** 535-547.

Siebert, S., F.T. Portmann, and P. Döll, 2010b: Global Patterns of Cropland Use Intensity. *Remote Sensing*, **2,** 1625-1643.

Singh, P., and L. Bengtsson, 2004: Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrological Processes*, **18,** 2363-2385.

Sitch, S., B. Smith, I.C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J.O. Kaplan, S. Levis, W. Lucht, M.T. Sykes, K. Thonicke, and S. Venevsky, 2003: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, **9,** 161-185.

Sivanappan, R.K., 1994: Prospects of micro-irrigation in India. *Irrigation and Drainage Systems*, **8,** 49-58.

Smakhtin, V., C. Revenga, and P. Doll, 2004: A Pilot Global Assessment of Environmental Water Requirements and Scarcity. *Water International*, **29,** 307-317.

Stehfest, E., L. Bouwman, D.P. van Vuuren, M.G.J. den Elzen, B. Eickhout, and P. Kabat, 2009: Climate benefits of changing diet. *Climatic Change*, **95,** 83-102.

Stone, R., and H. Jia, 2006: Hydroengineering - Going against the flow. *Science*, **313,** 1034-1037.

Strengers, B., R. Leemans, B. Eickhout, B. de Vries, and L. Bouwman, 2004: The land-use projections and resulting emissions in the IPCC SRES scenarios scenarios as simulated by the IMAGE 2.2 model. *GeoJournal*, **61,** 381-393.

Syvitski, J.P.M., C.J. Vörösmarty, A.J. Kettner, and P. Green, 2005: Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, **308,** 376-380.

Thenkabail, P.S., C.M. Biradar, P. Noojipady, V. Dheeravath, Y.J. Li, M. Velpuri, G.P.O. Reddy, X.L. Cai, M. Gumma, H. Turral, J. Vithanage, M. Schull, and R. Dutta, 2008: A Global Irrigated Area Map (GIMA) Using Remote Sensing at the End of the last Millenium, International Water Management Institute, 63 pp.

Tian, X., A. Dai, D. Yang, and Z. Xie, 2007: Effects of Precipitation-bias corrections on Surface Hydrology over Northern Latitudes. *Journal of Geophysical Research-Atmospheres*.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort, 2011: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108,** 20260-20264.

Tubiello, F.N., J.S. Amthor, K.J. Boote, M. Donatelli, W. Easterling, G. Fischer, R.M. Gifford, M. Howden, J. Reilly, and C. Rosenzweig, 2007: Crop response to elevated CO2 and world food supply - A comment on “Food for Thought...” by Long et al., Science 312 : 1918-1921, 2006. *European Journal of Agronomy*, **26,** 215-223.

Tuinenburg, O.A., R.W.A. Hutjes, C.M.J. Jacobs, and P. Kabat, 2010: Diagnosis of Local Land–Atmosphere Feedbacks in India. *Journal of Climate*, **24,** 251-266.

UN, 2010: World Population Prospects, the 2010 Revision, medium variant. D. o. E. a. S. A. United Nations, Ed.

USGS, 2000: HYDRO1k (available online at http://eros.usgs.gov/products/elevation/gtopo30/hydro/index.html). United States Geological Survey.

Voisin, N., A.W. Wood, and D.P. Lettenmaier, 2008: Evaluation of precipitation products for global hydrological prediction. *Journal of Hydrometeorology*, **9,** 388-407.

von Bloh, W., S. Rost, D. Gerten, and W. Lucht, 2010: Efficient parallelization of a dynamic global vegetation model with river routing. *Environmental Modelling & Software*, **25,** 685-690.

Vörösmarty, C.J., C.A. Federer, and A.L. Schloss, 1998: Evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling. *Journal of Hydrology*, **207,** 147-169.

Vörösmarty, C.J., B.M. Fekete, M. Meybeck, and R.B. Lammers, 2000a: Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution. *Journal of Hydrology*, **237,** 17-39.

Vörösmarty, C.J., B.M. Fekete, M. Meybeck, and R.B. Lammers, 2000b: Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. *Global Biogeochemical Cycles*, **14,** 599-621.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers, 2000c: Global water resources: Vulnerability from climate change and population growth. *Science*, **289,** 284-288.

Vörösmarty, C.J., C. Lévêque, and C. Revenga, 2005: Fresh Water. *Ecosystems and Human Well-Being: Current State and Trends.*, R. Hassan, R. Scholes, and N. Ash, Eds., Island Press.

Vörösmarty, C.J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J.P.M. Syvitski, 2003: Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change*, **39,** 169-190.

Vörösmarty, C.J., K.P. Sharma, B.M. Fekete, A.H. Copeland, J. Holden, J. Marble, and J.A. Lough, 1997: The storage and aging of continental runoff in large reservoir systems of the world. *Ambio*, **26,** 210-219.

Vrugt, J.A., C.G.H. Diks, H.V. Gupta, W. Bouten, and J.M. Verstraten, 2005: Improved treatment of uncertainty in hydrologic modeling: Combining the strengths of global optimization and data assimilation. *Water Resources Research*, **41,** W01017.

Wada, Y., L.P.H.v. Beek, C.M.v. Kempen, J.W.T.M. Reckman, S. Vasak, and M.F.P. Bierkens, 2010a: Global Depletion of Groundwater Resources.

Wada, Y., L.P.H. van Beek, and M.F.P. Bierkens, 2012: Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research*, **48**.

Wada, Y., L.P.H. van Beek, C.M. van Kempen, J.W.T.M. Reckman, S. Vasak, and M.F.P. Bierkens, 2010b: Global depletion of groundwater resources. *Geophysical Research Letters*, **37**.

Waha, K., L.G.J. van Bussel, C. Muller, and A. Bondeau, 2012: Climate-driven simulation of global crop sowing dates. *Global Ecology and Biogeography*, **21,** 247-259.

WCD, 2000: Dams and Development: A new framework for decision-making, The world commision on dams.

Weedon, G.P., S. Gomes, P. Viterbo, W.J. Shuttleworth, E.M. Blyth, H. Österle, J.C. Adam, N. Bellouin, O. Boucher, and M. Best, 2011: Assessing global potential evapotranspiration over land in the twentieth century using the WATCH Forcing Data. *Journal of Hydrometeorology*.

Wilby, R.L., J. Troni, Y. Biot, L. Tedd, B.C. Hewitson, D.M. Smith, and R.T. Sutton, 2009: A review of climate risk information for adaptation and development planning. *International Journal of Climatology*, **29,** 1193-1215.

Willmott, C.J., and K. Matsuura, 2001: Terrestrial air temperature and precipitation: monthly and annual time series (1950-1999) (version 1.02). *Centre*, Center for Climate Research, University of Delaware, Newark.

Wisser, D., S. Frolking, E.M. Douglas, B.M. Fekete, A.H. Schumann, and C.J. Vörösmarty, 2010: The significance of local water resources captured in small reservoirs for crop production - A global-scale analysis. *Journal of Hydrology*, **384,** 264-275.

Wisser, D., S. Frolking, E.M. Douglas, B.M. Fekete, C.J. Vorosmarty, and A.H. Schumann, 2008: Global irrigation water demand: Variability and uncertainties arising from agricultural and climate data sets. *Geophysical Research Letters*, **35**.

World Water Council, 2000: World Water Vision Commission Report: A water secure world, World Water Council.

WWAP, 2006: Water a shared responsibility. The United Nations World Water Development Report 2, New York.

Xie, P.P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society*, **78,** 2539-2558.

Yang, D.Q., B.S. Ye, and D.L. Kane, 2004: Streamflow changes over Siberian Yenisei River Basin. *Journal of Hydrology*, **296,** 59-80.

Yang, T., Q. Zhang, Y.D. Chen, X. Tao, C.Y. Xu, and X. Chen, 2008: A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River, China. *Hydrological Processes*, **22,** 3829-3843.

Ye, B.S., D.Q. Yang, and D.L. Kane, 2003: Changes in Lena River streamflow hydrology: Human impacts versus natural variations. *Water Resources Research*, **39,** 1200.

Annex A

Additional information for chapter 4

Material and methods

LPJmL global hydrology and vegetation model

We used the global hydrology and dynamic vegetation model LPJmL (Bondeau et al., 2007; Gerten et al., 2004; Sitch et al., 2003) in this study. The hydrology of LPJmL consists of a vertical water balance (Gerten et al., 2004) and a lateral flow component (Biemans et al., 2011; Rost et al., 2008) which are run at 0.5 degree resolution with daily timesteps. Each grid cell consists of a 2-layer soil column, in which water infiltrates and percolates. Water is evaporated directly from the first 20 cm of the upper soil layer, whereas transpiration takes place from both soil layers, depending on the root distribution of the vegetation in the cell. Runoff is calculated as the excess water above field capacity of the 2 soil layers plus the water percolating through the second layer. The lateral flow of runoff is calculated by a routing algorithm, which simulates the discharge at daily time steps by assuming a constant flow velocity of 1 m s^{-1} (Rost et al., 2008). Human alterations to natural river flow are included by the representation of irrigation withdrawals and supply (Rost et al., 2008) and the operation of large reservoirs, including the distribution of their water to irrigated areas (Biemans et al., 2011).

The net irrigation water demand on irrigated land is defined as the minimum of atmospheric evaporative demand and the amount of water needed to fill the soil to field capacity. The gross irrigation demand, or withdrawal demand is then calculated by multiplying the net irrigation demand with a country specific efficiency factor, reflecting the type of irrigation system (Rohwer et al., 2007). Part of the withdrawn water is lost during conveyance according to a country specific conveyance efficiency factor (Rohwer et al., 2007).

In grid cells where irrigation takes place, the irrigation demand is first withdrawn from the water stored in rivers and lakes within the grid cell. If this local availability is not sufficient, water is taken from an adjacent grid cell with the highest upstream area. If the demand is still not fulfilled, water can be supplied from an irrigation reservoir, if the grid cell is near to one (or more) reservoirs (Biemans et al., 2011). Finally, if there is no surface water available to fulfill the total irrigation demand, water can be taken from a source that is not explicitly specified in the model, which could be deep groundwater, or water transferred from other basins.

LPJmL does not represent the storage of deep groundwater, nor the extractions from those deep layers. Moreover, there is no global data available on the actual size of groundwater stocks. However, in many parts of the world, water for irrigation is taken from groundwater, and spatially explicit estimates of the fraction of irrigation water withdrawals from either renewable or fossil groundwater exist (Siebert et al., 2010). Based on our own calculations of gross irrigation requirements and fractions of irrigation that are supplied from groundwater (Siebert et al., 2010), current volumes of groundwater withdrawal are estimated at basin scale. For the future, we assumed in in each basin that groundwater extractions can be sustained at the current volume but must not exceed it.

The models' performance in the simulation of mean annual discharge was validated for 300 river basins across the world (Biemans et al., 2009) and improved by adding a reservoir operation module (Biemans et al., 2011). Calculation of irrigation withdrawals at global and continental scale were validated (Rost et al., 2008). A comparative study of global hydrological models showed that LPJmL performs well compared to state-of-the-art global hydrological models (Haddeland et al., 2011).

In contrast to other global hydrological models, LPJmL includes a full representation of the global carbon cycle, which makes the model suitable for studies on the interaction between water and vegetation. This representation consists of the simulation of the establishment, growth and mortality of natural vegetation (Sitch et al., 2003) and of both rainfed and irrigated agricultural vegetation (crops and pasture) (Bondeau et al., 2007). The model simulates the growth of crops by daily accumulation of carbon to four different carbon pools (roots, stems and mobile reserves, leaves and harvestable storage organs). The fraction of assimilated carbon allocated to the respective pools depends on the phenological stage of the crop, and is a function of heat unit accumulation. In case of water stress, the fraction allocated to leaves and storage organs is decreased. This influences both the total carbon uptake by not reaching optimal LAI shape, as well as the relative allocation to the harvestable storage organs, and therefore decreases the yield (Bondeau et al., 2007). The total attainable yield depends on the availability of water in the soil, temperature, radiation and soil properties. Actual yields are calibrated to FAO reported yields by adjusting country specific management settings as in Fader et al. (Fader et al., 2010).

For all crops, sowing dates are calculated based on crop-specific climatic thresholds and can therefore shift in time due to climate changes. The calculated sowing dates show good agreement with observed cropping calendars (Waha et al., 2012).

Climate change scenarios

The effect of climate change on water availability, irrigation water demand and crop production is calculated by forcing the model with bias-corrected climate scenarios of 3 GCMs (ECHAM5, IPSL4 and CNRM3) (Hagemann et al., 2011) for 2 IPCC-SRES emission scenarios A2 and B1 (Nakicenovic and Swart, 2000), developed in the EU-funded FP7 project WATCH (www.eu-watch.org). The forcing consists of daily fields of precipitation, mean surface-near air temperature, longwave downward and net shortwave radiation at 0.5 degree resolution. Bias correction on daily mean temperature and precipitation was done by a method developed by Piani et al. (2010) using observations from the Watch Forcing Data (Weedon et al., 2011).

Scenarios for the development of the food system

In order to feed a larger and wealthier population in 2100, an increase in total global food and feed crop production is needed. The International Institute for Applied Systems Analysis (IIASA) and the Food and Agricultural Organization (FAO) develop scenarios for the global food system, based on the Basic Linked System (BLS) model and the Global Agro-Ecological Zones model (GAEZ) (Fischer et al., 2002). This BLS-GAEZ model system accounts for international trade scenarios, the existing gap between actual and attainable yield, and the abundance of suitable land for agriculture to calculate regional crop production changes. The developed scenarios project trajectories of land use changes at 0.5 degree grid level (Figure 4.1a for global total, table A1 aggregated to basin scale) as well as yield increases for groups of countries and crops (Figure 4.1b for global average, table S1 for country and crop specific growth factors). Country groups (Figure A1) are chosen based on their similarity in economic and climatic conditions, and are expected to experience similar growth rates of crop yields in the future.

In this study projections of land use and yield growth for 2100 based on the SRES B1 and A2 storylines are used. Those scenarios were developed for the EU-funded FP7 WATCH project (www.eu-watch.org), but similar to previous projections (Fischer et al., 2005; Fischer et al., 2007). Those scenarios accounted for the effect of climate change on crop yields was accounted for, but water availability for irrigation was assumed available.

The land use patterns for 2000 and scenarios for 2100 consist of grid cell fractions of rainfed and irrigated cropland, but do not distinguish at grid cell level between different crops within this area. A dataset of fractional crop distributions (Fader et al., 2010) was used to disaggregate the total rainfed and irrigated area to different crop types. Relative crop distributions were therefore assumed to remain constant in the future.

Higher yielding crops will use more water than lower yielding crops, caused by a higher leaf area which increases photosynthesis and evaporation rates. As crop yields are projected to increase towards 2100, those higher yields and corresponding water use have to be taken into account. By combining the yield growth projections from the scenarios with reported yields for 1991-2000 (FAO, 2012a), crop and country specific yields for 2091-2100 were estimated, both for B1 and A2. Subsequently, LPJmL was calibrated to reproduce the projected yields for 2091-2100, by using the climate change scenario for 2091-2100 and the projected land use for 2100. Calibrations have been done for each GCM under the assumption that all the required irrigation water is available.

Model setup

Three types of model simulations were done to attribute irrigated crop production to different sources of water; rivers and lakes, reservoirs, and other sources:

1. Irrigated crops are only sustained by precipitation and surface water available in the natural system of lakes and rivers.
2. Irrigated crops are sustained by precipitation and surface water available in the natural system of lakes and rivers and managed reservoirs.
3. Irrigated crops are sustained by precipitation and irrigation water demand is always fulfilled, regardless of the source of this water.

Those three simulations were performed for the current land use (2000) and climate (1981-2000) and for the two sets of future land use (2100) and climate (2081-2100), all under climate forcing from the 3 GCMs.

Subsequently, irrigation supply from groundwater was estimated based on a global dataset providing estimates of the fraction of irrigation supplied from renewable and fossil groundwater within administrative units of different sizes (Siebert et al., 2010). These data were first aggregated to river basins, to estimate the fraction of irrigation demand supplied by groundwater at river basin level. Those basin-specific percentages were applied to our calculations of current (1981-2000) irrigation water demand to estimate volumes of irrigation water supply from groundwater. Subsequently, the same absolute volumes of groundwater supply per basin were assumed to be the maximum amount available in 2100 (2081-2100). The volume of irrigation water supply that cannot be withdrawn from surface water according to the model calculations, and is exceeding the estimated volume of groundwater extractions, was assumed to be unavailable, now and in the future.

Discussion

In the assessment of future water resources, conventional indicators of water stress mask potentially stressed regions. Those analyses are often based on comparisons of mean annual water demand and supply at basin scale (Alcamo and Henrichs, 2002; OECD, 2008). However, water can be available at the wrong time of a year (when water is needed in the dry period) or at the wrong place (when water is needed in the dry part of the basin). Moreover, the indicators in those studies do not address the effect of water stress on impacted sectors. The analysis performed in this study clearly reveals mismatches between supply and demand in both time and in place, because it is based on an integrated model which simulates both daily extractions and daily water availability at grid level. Moreover, it presents a quantitative assessment of the crop production losses related to eventual water shortage.

However, several uncertainties need more discussion.

Climate change scenarios

It is still very uncertain how the climate and land use will change in the future. To cover part of these uncertainties we selected two different emission scenarios and use the result of three different GCMs to force LPJmL. The use of more GCMs could reveal more uncertainty in the effect of climate change on irrigation water requirements (Konzmann et al., in revision). However, since we found that the main increase in irrigation demand will be caused by the expansion of irrigation area (Figures 4.1d and 4.2), we believe that adding more GCMs to our analysis would not change conclusions of the paper.

Land use change scenarios

For understanding uncertainty, it would have been better to use more agricultural scenarios than the BLS-GAEZ scenarios presented here. However, to our knowledge, this was the only set of scenarios that provide land use change for both irrigated and rainfed areas at 0.5 degree grids, and that project for 2100 consistent with B1 and A2 emission scenarios. The scenarios presented by Molden et al. (2007) do account for water availability, but calculate water demand and availability at (sub)basin level (de Fraiture, 2007). Moreover, these scenarios present outlooks for 2050 only. In their most water efficient scenario (The 'Comprehensive Assessment of Water Management in Agriculture scenario') they project a 16% increase of irrigated area up to 2050, which is lower than in the here used scenarios (26-29% in 2050 for B1-A2). However, in an 'irrigation scenario' which emphasizes food self-sufficiency and food supply increase by irrigation area expansion, a 33% increase in irrigated area towards 2050 is projected. Other agricultural studies whose simulation period extends to 2100 simulate land use changes at 0.5 degree, but without considering any changes in irrigated areas (IMAGE-team, 2001).

Groundwater withdrawal

It is very difficult to make a good estimate of the amount of groundwater withdrawals for irrigation, especially to make a distinction between extractions from relatively shallow groundwater, from which withdrawals can be regarded as sustainable as they are continuously being recharged, and extractions from deep (fossil) groundwater which are depleting reserves that have been filled up in hundreds or thousands of years.

There is some inconsistency in the definition of groundwater between LPJmL and the data we used to estimate groundwater withdrawals. LPJmL does not simulate groundwater recharge, and water percolating through the second soil layer is added to runoff without time delay. Therefore, the surface water in LPJmL technically contains the sustainable part of groundwater, but is underestimating its supply because of the lack of representation of storage. Consequently, to consider all water extractions that cannot be supplied from surface water as unsustainable is an overestimation. The dataset on groundwater extraction used in this study (Siebert et al., 2010) does not distinguish between shallow and deep groundwater extractions, and we used this data to constrain the otherwise unlimited supply that LPJmL generates if surface water has run out. Therefore we do not consider our methodology suitable to judge whether groundwater extractions are sustainable.

However, the assumption that groundwater withdrawal can be sustained at current volumes in every basin is not realistic, especially in heavily irrigated basins in India and China where groundwater tables are rapidly declining (Rodell et al., 2009; Stone and Jia, 2006). On the other hand, in regions where groundwater extractions are currently very low, but where irrigation is expected to increase, like the Mekong, Zambezi and Niger, additional groundwater reserves may be available and used (MacDonald et al., 2012). From that perspective, the results in this study should be interpreted using regional information.

CO_2 fertilization

Higher atmospheric CO_2 concentrations will usually increase plant production and improve water use efficiency However, the exact dimension of this effect under non-optimal field conditions and at the concentrations projected for 2100, is still unclear (Ewert et al., 2007; Long et al., 2006; Tubiello et al., 2007). LPJmL simulates a relatively strong impact of elevated CO_2 concentrations on vegetation production and water use efficiency and might therefore underestimate the water demands for 2100 in some regions – in particular where nutrient limitations (not explicitly simulated) outdo, or lessen, beneficial CO_2 effects. Without accounting for the CO_2 effect, the water demand for irrigation is projected to be 8-19 % higher (for B1-A2 2081-2100) (Figure 4.1d). The simulated effect of CO_2 on crop yields is particularly strong for rainfed crops, where yields would be 21-33% lower (B1-A2 for 2081-2100) if CO_2 effects were not accounted for. For irrigated crops the production would be 9-14% lower (B1-A2). Although the uncertainty in model results caused by the uncertainty in the strength of the CO_2 effect is very large, it does not affect this study's conclusion that water needed for irrigation by the end of the century may not be available which will cause lower-than-projected crop production. Since the CO_2 effect is likely to be less strong in reality than simulated by LPJmL, especially in poorly managed systems, we present here the most optimistic scenario regarding CO_2 'fertilization'.

Withdrawals by other users

Although agriculture is and will be the largest water consumer at global scale, water withdrawals for other sectors are projected to increase as well (Alcamo et al., 2007). Moreover, there is a minimum amount of water needed to sustain aquatic ecosystems (environmental flow requirement) (Smakhtin et al., 2004). These water requirements are not taken into account in this study, but could potentially put food production under further pressure in some regions.

Rainfed agriculture

The focus of this study is water scarcity in irrigated agriculture. This might suggest that rainfed agriculture will face less risk with respect to water scarcity in the future. However, the contrary may be true as rainfed agriculture and yields are more directly prone to climate change. However, the effect of climate change on rainfed agriculture was addressed in previous studies (Rost et al., 2009; Schmidhuber and Tubiello, 2007) and also accounted for in the agricultural scenarios used in this study (Fischer et al., 2005).

Further, all analyses presented here show mean annual average water demand, supply and crop production. Intra-annual variability, which often produces yield losses in rainfed agriculture if no water storage systems are in place, might therefore reveal lower food production in (successions of) dry years than suggested in this study.

Improvement of water infrastructures

We assumed that the current human-built dams and reservoirs stay in function and that no new reservoirs are being built. However reservoirs tend to loose capacity because of sedimentation (Vörösmarty et al., 2003) and there are already many dams planned to be built in the coming decades (Grumbine and Xu, 2011).

Further there are no scenarios for an improvement of irrigation systems taken into account. However, with the introduction of new irrigated areas and under pressure of growing water scarcity, irrigation efficiency can probably increase in some regions of the world.

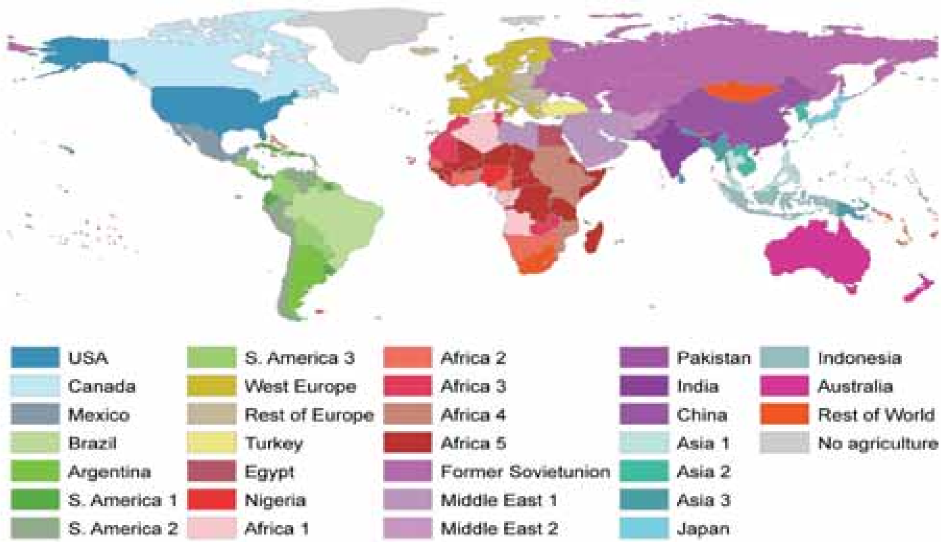


Figure A1. Groups of countries that are expected to experience same growth in productivity.

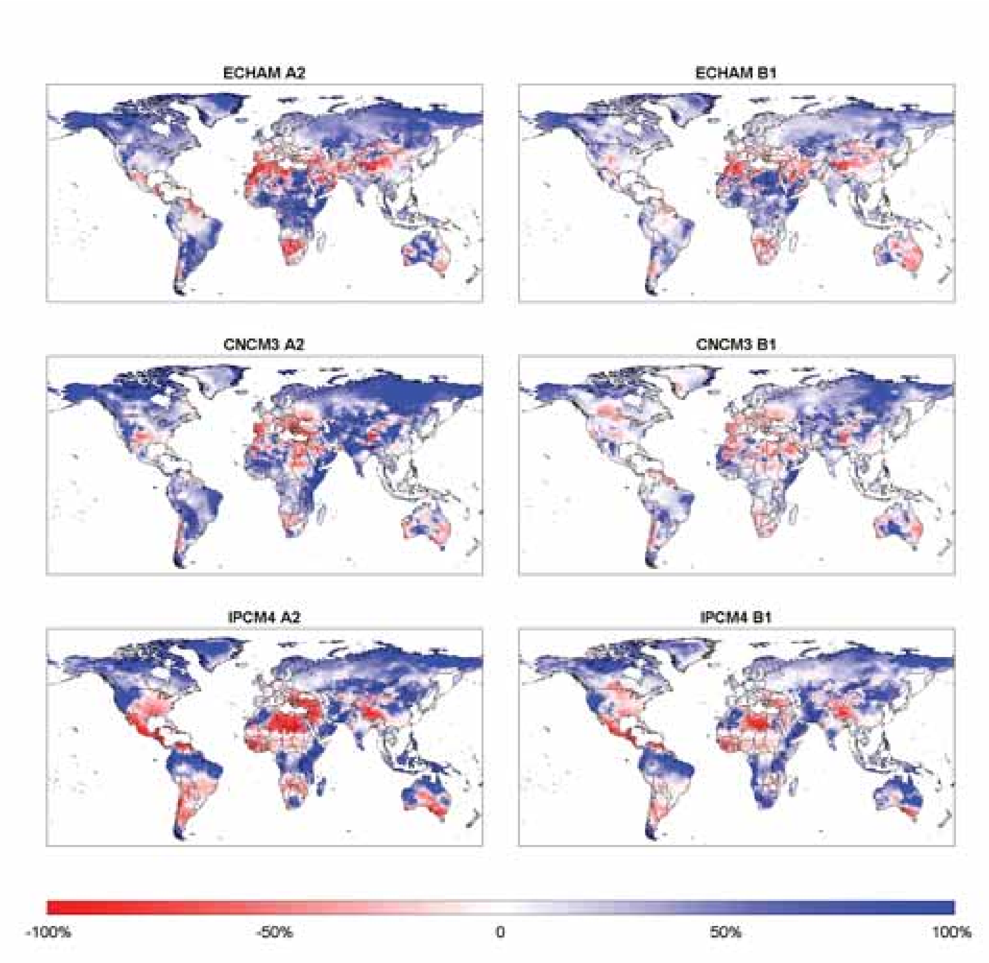


Figure A2. LPJmL-simulated relative changes in mean annual discharge (2081-2100 with respect to 1981-2000) for the 3 GCMs and 2 emission scenarios.

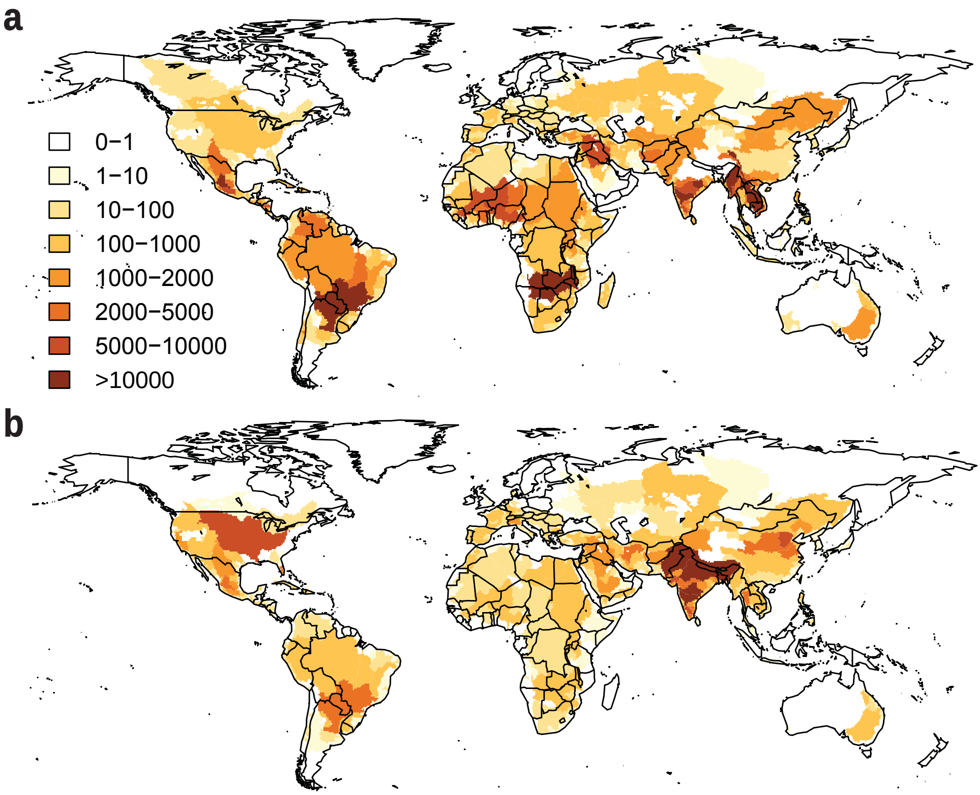


Figure A3. Most vulnerable regions. (a) Distribution of the mean annual reduction in crop production due to irrigation water deficits (in kt DM year^{-1}), accumulates to 460 Mt (A2, 2081-2100)
(b) Distribution of the mean annual crop production relying on groundwater (in kt DM per year), accumulates to 339 Mt globally (A2, 2081-2100).

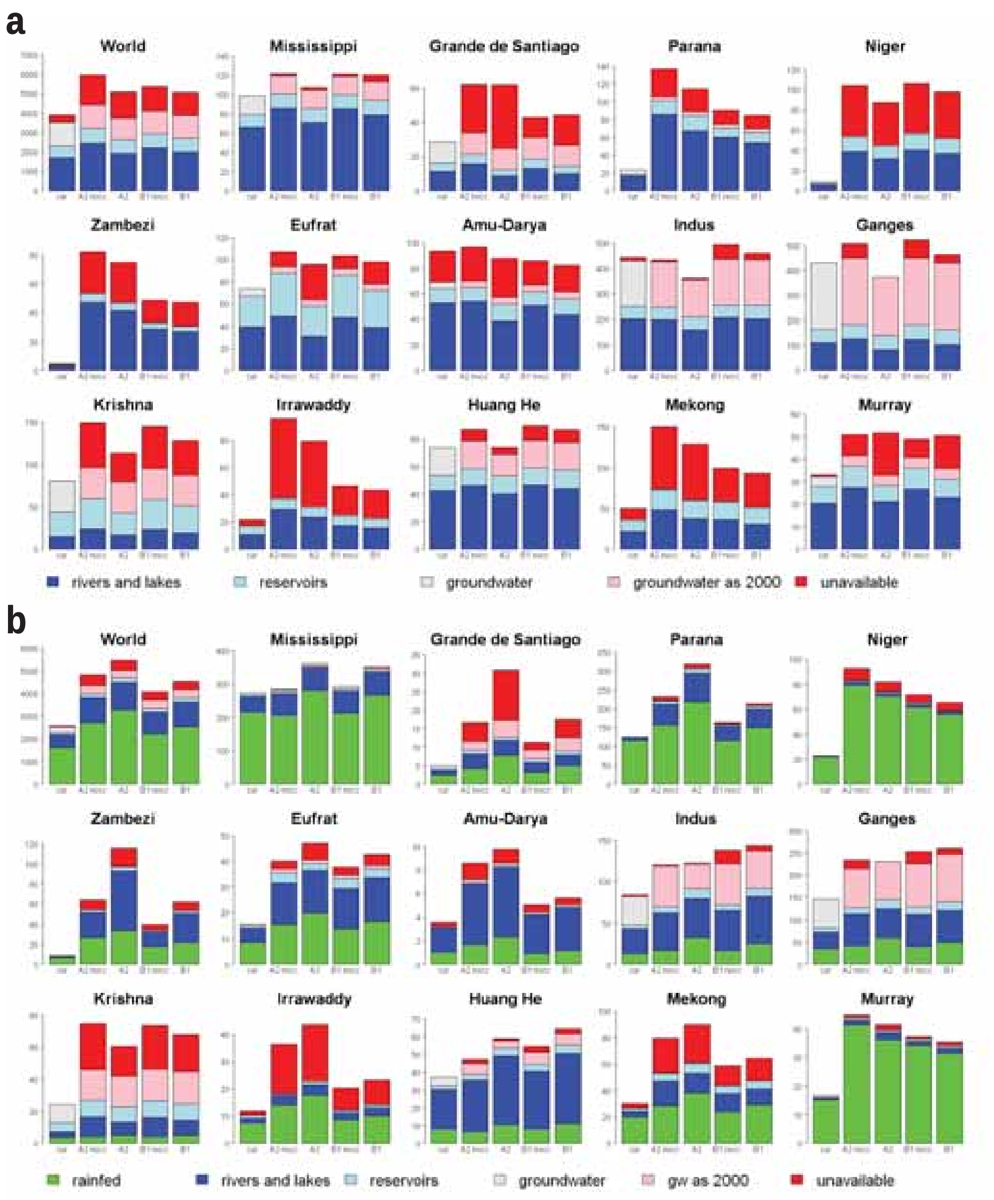


Figure A4. (a) Irrigation water demand in km^{3}yr^{-1}, global and for a selection of river basins. Bars represent the current (1981-2000) and future (2081-2100) demand with and without climate change effect and for A2 and B1 scenarios. Colours show the potential fulfilment of this demand from different water sources: dark blue volumes can be extracted from natural rivers and lakes, light blue from human build reservoirs, grey from groundwater, pink from groundwater if supply is sustained, red volumes are unavailable.
(b) As S4a but for crop production in Mt yr^{-1}. Green represents rainfed crop production, the sum of other colors represents irrigated production. Colors of water sources as in S4a. All bars are the average of simulations with 3 GCMs.

Table A1. Rainfed and irrigated cropland extentfor selected river basins in 2000 and 2100 according to agricultural scenarios

	2000		2100 A2				2100 B1			
	rainfed	irrigated	rainfed		irrigated		rainfed		irrigated	
	10^3 km^2	10^3 km^2	10^3 km^2	% Δ	10^3 km^2	% Δ	10^3 km^2	% Δ	10^3 km^2	% Δ
Mississippi	1016.9	127.3	977.9	-3.8	161.3	26.7	981.7	-3.5	160.6	26.1
Grande de Santiago	15.8	12.1	23.8	50.6	22.8	87.8	15.9	0.7	15.8	30.8
Parana	408.0	14.3	524.4	28.5	86.7	504.3	411.3	0.8	57.2	299.2
Niger	354.2	4.7	483.4	36.5	44.2	839.8	388.0	9.6	43.6	827.6
Zambezi	134.1	3.0	219.9	63.9	50.6	1590.9	136.0	1.4	28.5	854.3
Eufrat	101.1	57.5	119.6	18.3	74.8	30.1	100.5	-0.6	72.5	26.1
Amu-Darya	25.2	44.8	22.5	-10.7	46.0	2.7	10.5	-58.3	38.4	-14.2
Indus	129.0	213.3	125.3	-2.9	200.3	-6.1	124.2	-3.7	222.3	4.2
Ganges	390.6	299.2	344.1	-11.9	359.1	20.0	324.0	-17.1	356.7	19.2
Krishna	114.4	39.8	104.5	-8.7	73.7	85.4	101.3	-11.4	71.3	79.3
Irrawaddy	60.9	13.8	71.7	17.7	56.5	310.3	45.7	-25.1	27.8	102.2
Huang He	108.2	69.9	75.3	-30.4	82.1	17.6	82.8	-23.5	82.9	18.6
Mekong	125.1	24.5	135.2	8.1	71.7	192.5	100.7	-19.5	44.4	81.2
Murray	198.6	14.4	198.3	-0.1	22.1	53.5	200.3	0.9	21.2	47.2
WORLD	12834.4	2756.4	14643.9	14.1	3974.1	44.2	12289.4	-4.2	3598.8	30.6

Table A2. Projected yield growth per crop and country group (yields in 2100 as relative to yields in 2000 according to the A2 scenario)

	wheat	rice	other grain	protein feed	other food
USA	1.3	1.8	1.6	1.8	1.7
Canada	2.3	1.0	2.3	3.3	2.8
Mexico	1.2	1.2	3.7	2.1	1.4
Brazil	2.3	1.6	1.7	1.3	1.4
Argentina	1.6	3.4	1.7	2.1	1.9
S. America 1	4.5	3.2	4.3	2.9	2.5
S. America 2	3.7	3.3	5.1	3.8	2.6
S. America 3	2.8	2.7	4.7	2.6	2.6
Western Europe	1.2	2.0	1.7	1.1	1.3
Rest of Europe	1.8	2.7	2.1	2.3	2.4
Turkey	1.4	0.9	4.9	2.9	1.8
Egypt	2.4	3.2	3.2	2.3	1.9
Nigeria	1.3	2.5	3.5	2.2	2.5
Africa 1	4.6	4.4	6.4	3.1	3.6
Africa 2	1.2	4.0	3.5	3.1	2.5
Africa 3	3.6	5.0	4.5	3.7	3.0
Africa 4	3.3	5.4	4.7	4.2	3.6
Africa 5	3.3	5.4	5.7	4.3	4.2
Former Soviet union	1.9	1.9	1.9	1.9	1.9
Middle East 1	4.3	3.3	5.1	3.7	3.2
Middle East 2	5.2	5.6	4.9	6.9	6.3
Pakistan	2.3	1.9	7.2	2.3	2.1
India	0.7	1.5	1.4	1.5	3.5
China	1.4	1.7	1.9	2.3	2.4
Asia 1	1.0	3.6	5.5	2.4	2.6
Asia2	2.1	2.7	2.8	2.3	1.9
Asia 3	2.4	2.9	3.4	2.4	2.4
Japan	2.7	1.4	1.1	0.7	0.9
Indonesia	1.0	1.5	2.3	1.9	2.3
Australia	1.9	1.5	3.9	1.7	2.2
Rest of World	3.4	2.8	3.2	3.3	3.2
WORLD	1.5	1.9	2.0	1.8	2.2

Table A3. Translation between crop groups of BLS-GAEZ, LPJmL and FAO

BLS-GAEZ	LPJmL	FAO crops for calibration
wheat	temperate cereals	wheat
rice	rice	rice paddy
other grain	maize	maize
other grain	tropical cereals	millet
other grain	pulses	peas dry, peas green, lentils
other food	temperate roots	sugarbeet
other food	tropical roots	sweet potatoes, cassava
protein feed	oil crops sunflower	sunflower seeds
protein feed	oil crops soybean	soybean
protein feed	oil crops groundnut	groundnut in shell
protein feed	oil crops rapeseed	rapeseed
other food	sugarcane	sugarcane

Summary

Driven by a growing food demand during the 20th century, people have increased the level of control over the hydrological cycle in order to make more water available at the time and place needed. During the last 50 years, the global irrigated area roughly doubled and the amount of water used by the agricultural sector grew substantially. In the same time the construction of large dams has increased the usable volume of water. Altogether, the cumulative capacity of large reservoirs is 8000 km^3, which is 20% of the global annual runoff. Around the year 2000 a third of the total global crop production was harvested from irrigated lands, that occupied less than a fifth of the total agricultural area. It is estimated that 30-40% of the irrigated areas worldwide rely on water from reservoirs and that those reservoirs contribute to 12-16% of the world food production. Both the expansion of irrigation and construction of reservoirs have therefore been of major importance for the increase in the world food production over the 20th century.

However, there is reason for concern because there is a limit to the amount of freshwater that can be exploited sustainably. About one third of the world's population is already living in countries suffering from water stress. The global population is projected to further increase towards 9 to 12 billion in this century. Accompanied with expected economic growth, this will result in higher global water demands. In addition, climate change will affect both water availability and demand. It is questionable if sufficient water resources will be available to sustain a further growing future food production.

The general objective of this thesis is to assess the combined effect of future socio-economic and climate changes on agricultural water supply and demand, including the associated effects on crop production in the coming century. Therefore the global simulation model LPJmL was used. This model simulates hydrology, crop growth and their interlinkages at global scale and is therefore very suitable to perform studies on water resources in relation to food production. To test the simulation of water availability, the hydrological component of LPJmL was validated by comparing simulated discharge with observed time series of river discharge for almost 300 rivers (chapter 2). To reflect input uncertainty, the model was used in combination with seven different global gridded precipitation datasets that were based on observed precipitation. It is shown that the uncertainty in precipitation input at basin level is large, especially in mountainous, arctic and small basins. This uncertainty is amplified in the simulated discharge. For almost half of the basins the observed discharge falls within the uncertainty range of simulated discharge, which complicates proper validation and calibration.

However, in several basins precipitation uncertainty alone could not explain all the differences between observed and simulated discharge. There are basins where simulated mean annual

discharge is higher than observed discharge for all precipitation datasets, but also basins that show a mismatch in the timing of flow between simulations and observations. These differences are mostly attributed to the effect of human alterations of the global water cycle, that are reflected in the observations reporting actually measured discharge, but not in the simulations that reflect 'naturalized' flow, without accounting for the effect of withdrawals and operations of large reservoirs.

The development and testing of a reservoir operation scheme for LPJmL is described in chapter 3. This scheme accounts for the effect of reservoir management on streamflow and water supply to agriculture for around 7000 dams around the globe. The simulation of discharge in impacted basins improved after implementation of this scheme. At continental scale, the combined effect of reservoir operation and irrigation withdrawals decreases the mean annual discharge to oceans and changes the timing of this discharge. In North America, Europe and Asia, in specific spring and summer months, discharge is up to 10% lower than it would be in the natural flow. At the end of the 20th century, reservoir operations and irrigation withdrawals decreased mean annual global discharge by about 2% per year (930 km^3 yr^{-1}).

Subsequently, the contribution of large reservoirs to irrigation water supply during the 20th century was estimated. Simulation results show that by the end of the 20th century water from reservoirs fulfilled 17% of the global agricultural water demand (around 460 km^3 yr^{-1}). This is more than a quarter of the total surface water supply to irrigation.

Irrigated areas that rely heavily on water supply from reservoirs are for example situated in the Colorado and Columbia basins in the US, and several large basins in India, China and Central Asia.

Future threats to irrigation water supply and related food production are investigated in Chapter 4. To account for climate input uncertainty, climate change projections of 3 GCMs and two emission scenarios (B1 and A2 SRES) were used. Land use change scenarios representing socio economic storylines for the same development paths were implemented (B1 and A2).

Expansion of irrigated area and an intensification of agriculture projected in the land use change scenarios are needed to meet future food demand. This will result in higher irrigation water demand. By comparing the increased water demand with future availability in rivers, lakes, reservoirs and groundwater, it is estimated that roughly 25% of the irrigation water demand in 2100 will not be met. This irrigation water shortage can result in a reduction of annual global irrigated food crop production of around 20% (400 Mt dry matter). Regions where the irrigated crop production will be most at risk include basins in Southern Africa and South Asia, where irrigated production reductions might be over 50%. Improved management of water resources and more water efficient agriculture is needed to secure the crop production that might become at risk because of water shortage.

The potential effect of better water resources management was evaluated for five large river basins on the Indian subcontinent (chapter 5). This region faces a population increase from 1.6 billion in 2000 towards 2 billion around 2050 and a rapid economic growth. Although almost all land suitable for agriculture is already occupied, land use scenarios still project that expansions of irrigated areas combined with yield increases are needed to achieve the required food production. The pressure on available water resources is already high, illustrated by the observed fast decline of groundwater tables at some locations. The influence of climate change on monsoon precipitation and glacier volume is still uncertain. For five large basins, an assessment of future water scarcity and the effects on crop production is made, in the presence or absence of two adaptation measures. Both adaptation measures focused at decreasing water shortage: increasing storage capacity in large reservoirs and improving the overall irrigation efficiency. Simulation result showed that with additional improvements to the water infrastructure, a larger part of the crop production can be secured. The best solution, however, differs per basin. Large scale models like LPJmL are suitable to perform quick scans to identify regions where future food production might become at risk due to water shortages, but more detailed analysis is required for the actual design of those adaptation measures.

Chapter 6 contains an analysis and discussion of the main sources of uncertainty and limitations affecting the results presented in this thesis and assessments of agricultural water resources in general. The most important uncertainties relate to the quantification of the amount of groundwater available for irrigation, the effect of rising CO_2 concentrations on crop growth and water demand, and the future land use patterns. Multi data, multi model approaches can help identifying, quantifying and reducing those uncertainties. It is shown that despite these uncertainties and limitations, the main conclusions of this thesis are still valid.

This thesis shows that there is a clear need for a consideration of water limitations in agricultural assessments and future outlooks. Due to higher future food demands and increased water scarcity the water and agricultural sectors will become even more linked in the future. In too many agricultural studies water limitation is still ignored or underestimated, leading to unrealistic projections of future food production.. This thesis shows that a shortage in irrigation water availability will constraint future food production, unless measures are taken to improve water use efficiency or enhance water infrastructure.

Samenvatting

Om aan de stijgende voedselvraag te voldoen, is in de afgelopen 50 jaar het geïrrigeerde landbouwareaal wereldwijd verdubbeld. Op dit moment is ongeveer één derde van de totale mondiale gewasproductie afkomstig van geïrrigeerde gebieden, hoewel die minder dan één vijfde van het totale landbouwareaal beslaan. De hoeveelheid water beschikbaar voor irrigatie is verhoogd door de constructie van grote stuwmeren (reservoirs). Naar schatting wordt op 30-40% van de geïrrigeerde gebieden water uit reservoirs gebruikt en deze reservoirs dragen bij aan 12-16% van de huidige wereldvoedselproductie. De totale capaciteit van deze reservoirs is inmiddels rond de 8000 km^3; dat is gelijk aan 20% van de jaarlijkse totale wereldwijde rivierafvoer. Zowel de uitbreiding van het geïrrigeerde gebied als de bouw van grote reservoirs zijn daarom van groot belang geweest voor de toename van de wereldvoedselproductie in de 20ste eeuw.

Er zit echter een grens aan de hoeveelheid zoetwater die duurzaam gebruikt kan worden. Een derde van de wereldbevolking leeft in landen die nu al kampen met periodes van waterschaarste. De wereldbevolking zal deze eeuw verder stijgen tot 9 à 12 miljard mensen, en de gemiddelde welvaart zal naar verwachting toenemen. Dit zal dit leiden tot een hogere voedsel- en dus watervraag. Daarnaast zal klimaatverandering invloed hebben op de waterbeschikbaarheid en -vraag. Het is onzeker of er voldoende water zal zijn om in de groeiende vraag naar voedsel te voorzien.

Het belangrijkste doel van dit proefschrift is het in kaart brengen van het gecombineerde effect van sociaaleconomische ontwikkelingen en klimaatverandering op de vraag en beschikbaarheid van water voor de landbouw in de 21ste eeuw. Daarnaast worden de effecten van potentiële watertekorten op de wereldvoedselproductie gekwantificeerd. Hiervoor is gebruik gemaakt van het mondiale computermodel LPJmL dat de relatie tussen klimaat, waterkringlopen en gewasproductie simuleert.

Om de betrouwbaarheid van de door het model berekende waterbeschikbaarheid te testen, wordt allereerst in hoofdstuk 2 de hydrologische component van LPJmL gevalideerd. Dit gebeurt door gesimuleerde rivierafvoer te vergelijken met gemeten tijdseries van rivierafvoer op de locaties van bijna 300 meetstations wereldwijd. Het model is toegepast in combinatie met zeven verschillende datasets van de mondiale neerslag. Al deze datasets zijn gebaseerd op gemeten neerslag van meetstations en satellieten, maar verschillen in de hoeveelheid gebruikte meetgegevens en de interpolatie-methoden. De onzekerheid in neerslag op stroomgebiedsniveau blijkt erg groot te zijn, met name voor stroomgebieden in bergachtig gebied, rond de Noordpool en in relatief kleine stroomgebieden. Voor bijna de helft van de bestudeerde stroomgebieden valt de gemeten rivierafvoer binnen de onzekerheidsmarge van de gesimuleerde afvoer. Dit compliceert een goede validatie en kalibratie van het model.

Toch kan voor veel stroomgebieden neerslagonzekerheid alléén niet alle verschillen tussen de gesimuleerde en gemeten afvoer verklaren. Er zijn stroomgebieden waar het model de jaargemiddelde afvoer overschat voor alle gebruikte neerslag datasets. Er zijn ook stroomgebieden waar de timing van de gesimuleerde afvoer niet overeenkomt met de metingen. Beide verschillen kunnen voor een groot deel worden toegeschreven aan het effect van menselijke ingrepen in de natuurlijke waterkringloop, zoals wateronttrekkingen voor irrigatie en het beheer van grote dammen. Het effect van deze ingrepen is wel zichtbaar in de gemeten afvoer reeksen, maar niet in de simulaties die de ‘natuurlijke afvoer’ nabootsen.

De ontwikkeling en validatie van een reservoir-algoritme is beschreven in hoofdstuk 3. Dit algoritme simuleert de effecten van reservoirbeheer op rivierafvoer en watervoorziening in de geïrrigeerde landbouw voor ongeveer 7000 dammen wereldwijd. De implementatie van het algoritme verbetert de simulatie van rivierafvoer in rivieren met grote reservoirs. Modelresultaten laten zien dat reservoirbeheer en water-onttrekkingen voor irrigatie leiden tot een afname van de jaargemiddelde rivier afvoer naar oceanen. Bovendien wordt de timing van deze afvoer anders. In sommige lente- en zomermaanden is in Noord-Amerika, Europa en Azië de totale continentale afvoer tot 10% lager dan die zou zijn in de natuurlijke situatie. Rond het eind van de 20ste eeuw zorgden reservoirs en onttrekkingen ten behoeve van irrigatie voor een vermindering van de totale mondiale jaargemiddelde afvoer naar de oceanen met 2% per jaar (930 km^3 jaar^{-1}).

In hoofdstuk 3 is tevens een inschatting gemaakt van de bijdrage van grote reservoirs aan watervoorziening voor irrigatie. De modelresultaten laten zien dat aan het eind van de 20ste eeuw 17% van de totale waterbehoefte voor irrigatie kon worden vervuld door water uit reservoirs (ongeveer 460 km^3 jaar^{-1}). Dit is meer dan een kwart van het totale volume aan oppervlaktewater dat gebruikt wordt voor irrigatie. Geïrrigeerde gebieden die erg afhankelijk zijn van watertoevoer uit reservoirs liggen bijvoorbeeld in de stroomgebieden van de Colorado en Columbia in de Verenigde Staten, en verschillende grote stroomgebieden in India, China en Centraal-Azië.

In hoofdstuk 4 wordt onderzocht of en hoe watertekorten in de toekomst de irrigatiewater-voorziening en de gerelateerde voedselproductie zullen bedreigen. Om rekening te houden met de onzekerheid met betrekking tot klimaatverandering, is daarvoor gebruik gemaakt van klimaatveranderingsscenario’s uit 3 mondiale klimaatmodellen (GCM’s) voor 2 emissiescenario’s (SRES A2 en B1). Verder is gebruik gemaakt van twee landgebruiksscenario’s gebaseerd op dezelfde verhaallijnen (SRES A2 en B1).

De landgebruiksscenario’s voorzien een uitbreiding van het totale mondiale geïrrigeerde gebied en een verdere intensivering van de landbouw om aan de toekomstige voedselvraag te kunnen voldoen. Dit zal resulteren in een grotere watervraag. Deze grotere watervraag is vergeleken met de toekomstige beschikbaarheid van water in rivieren, meren, grote reservoirs en grondwater. Er wordt geschat dat aan ruwweg 25% van de irrigatiewatervraag in 2100 niet kan worden voldaan. Dit tekort aan irrigatiewater kan leiden tot een reductie van de wereldwijde geïrrigeerde gewasproductie van rond de 20% (400 Mt droge stof). De geïrrigeerde gewasproductie loopt het grootste risico in stroomgebieden in zuidelijk Afrika en Zuid-Azië, waar verliezen kunnen oplopen tot meer dan 50%. Een beter beheer van waterbronnen en een efficiënter watergebruik in de landbouw is daarom nodig om productie in risicovolle gebieden veilig te stellen.

Het potentiële effect van verbeterd waterbeheer is geëvalueerd voor vijf grote stroomgebieden op het Indiase subcontinent (hoofdstuk 5). In deze regio zal de bevolking toenemen van 1,6 miljard in 2000 tot 2 miljard in 2050. Daarnaast wordt een snelle economische groei verwacht. Bijna al het land dat geschikt is voor landbouw is al in gebruik. Toch zal, naast een opbrengstverhoging op huidig areaal, ook een verdere uitbreiding van geïrrigeerd gebied plaats moeten vinden om de benodigde voedselproductie te kunnen halen. Dit zal leiden tot een hogere waterbehoefte. De druk op beschikbare waterbronnen is echter al hoog, en wateronttrekkingen zijn niet overal duurzaam. Bovendien is de invloed van klimaatverandering op moessonregens en gletsjervolumes nog erg onzeker.

Voor de vijf grote stroomgebieden is een schatting gemaakt van de toekomstige waterschaarste en de effecten daarvan op gewasproductie, in de aanwezigheid of afwezigheid van twee adaptatiemaatregelen. Beide maatregelen richten zich op het verminderen van waterschaarste: een verhoging van de opslagcapaciteit van grote reservoirs en een verbetering van de irrigatie-efficiëntie. Modelresultaten laten zien dat met behulp van verbeteringen in de waterinfrastructuur een groter deel van de gewasproductie veiliggesteld kan worden. De beste oplossing verschilt echter per stroomgebied. Uit deze studie blijkt dat grootschalige modellen zoals LPJmL geschikt zijn om relatief snel regio's aan te wijzen waar de toekomstige voedselproductie in gevaar zou kunnen komen door watertekorten. Een gedetailleerdere studie is echter noodzakelijk voor het daadwerkelijk ontwerpen van de adaptatiemaatregelen.

Hoofdstuk 6 bevat een algemene discussie van de resultaten van dit proefschrift en aanbevelingen voor verder onderzoek naar de relatie tussen water en voedselproductie. De belangrijkste onzekerheden in resultaten hebben betrekking op het kwantificeren van de hoeveelheid grondwater die beschikbaar is voor irrigatie, het effect van stijgende CO_2-concentraties op gewasgroei en watervraag, en het toekomstig landgebruik. Het gebruik van meerdere invoerdatasets en meerdere modellen kan in verder onderzoek helpen bij het identificeren, kwantificeren en reduceren van onzekerheden. Toch zijn, ondanks onzekerheden en beperkingen van het onderzoek, de belangrijkste conclusies van het proefschrift robuust.

Dit proefschrift toont duidelijk aan dat het noodzakelijk is om rekening te houden met fysieke grenzen aan zoetwatergebruik in studies naar de toekomstige voedselvoorziening. Door de stijgende voedselvraag en grotere waterschaarste zullen de water- en landbouwsectoren nog meer verweven worden in de toekomst. In veel landbouw-toekomstverkenningen wordt de beperkte watervoorraad genegeerd of onderschat, waardoor de schattingen van toekomstige voedselproductie niet realistisch zijn. Dit proefschrift laat zien dat een tekort aan beschikbaar water de voedselproductie zal gaan beperken, tenzij er maatregelen worden genomen om watergebruik efficiënter te maken of de waterinfrastructuur te verbeteren.

Dankwoord & Acknowledgements

De afgelopen jaren heb ik met heel veel plezier aan mijn onderzoek gewerkt, en in jullie handen ligt het resultaat. Ik heb ontzettend veel geleerd, ben gegroeid als wetenschapper, en hopelijk ook als persoon. Natuurlijk wist ik van tevoren dat het schrijven van een proefschrift pieken zou gaan kennen en dalen, maar vooral de laatste maanden waren erg heftig. Op deze pagina's wil ik mij richten tot al die mensen die ertoe hebben bijgedragen dat ik hier nu sta.

In de eerste plaats ben ik heel veel dank verschuldigd aan Pavel Kabat en Tom Kram. Dank jullie wel voor jullie inzet die het voor mij mogelijk maakte om dit onderzoek op deze manier te doen, als gezamenlijk PBL en WUR project. Het duurde even voordat het groene licht kwam, maar toen kon ik ook precies datgene gaan doen waar mijn hart ligt. Ik heb er nooit spijt van gehad! Hoewel ik het soms een uitdaging vond om twee werkplekken te hebben (twee keer zoveel mensen met ideeën, twee keer zoveel collega's..) , vond ik het over het algemeen een verrijking. Ik was mij er altijd van bewust hoe mijn onderzoek zou passen in het grote IMAGE-plaatje en vond het motiverend die toepassing zo duidelijk voor ogen te kunnen houden.

Mijn begeleiders Ronald en Fulco, dank jullie wel voor alle hulp en advies die ik van jullie heb gekregen. Ronald, jij hebt mij in het begin geholpen mijn gedachten te ordenen, zelfvertrouwen te kweken en te zorgen dat er een gestructureerd onderzoeksplan kwam. In Treignac heb je me ontzettend geholpen met het schrijven van mijn eerste paper, maar heb ik ook ontdekt dat ik in de keuken ook nog heel veel van je kan leren. Samen hebben jullie altijd met mij meegedacht over onderzoeksopzet en planning, en heel zorgvuldig en kritisch mijn manuscripten van commentaar voorzien. Fulco, jou wil ik nog graag nadrukkelijk bedanken voor de momenten van crisismanagement tijdens de afgelopen maanden.

Pavel, ik vond het ontzettend inspirerend om met jou samen te werken. In de loop van de jaren werden onze discussies steeds interessanter en intenser. Jij leerde mij kritisch naar mijn werk te kijken en wees mij feilloos op de zwakke plekken in redeneringen en verhaallijnen. Dank je wel voor je vertrouwen en voor de leuke brainstormsessies die hielpen mijn ideeën vorm te geven.

Arjen Hoekstra, Elke Stehfest, Remko Uijlenhoet and Charles Vörösmarty, I am happy that you are willing to be a member of the thesis committee and I hope you enjoyed the reading.

Bij het PBL heb ik mij altijd welkom gevoeld. Rineke, toen ik dertien jaar geleden voor het eerst binnenwandelde, was jij al warm en hartelijk, en nog steeds ben jij degene die met enthousiasme iedereen optrommelt voor een kop thee. De IMAGE workshops waren steeds

motiverend omdat we met een groep naar een doel toe werkten. En Elke, jij was altijd bereid mij feedback te geven op manuscripten, ideeën en plannen. Kathleen en Lenny, de andere 'IMAGE-AIO's', het was fijn met jullie ervaringen te delen.
Mijn collega's in Wageningen zorgden voor de goede werksfeer en hebben mij op verschillende manieren erg ondersteund. Olaf en Petra, het was leuk om met jullie samen de weg te zoeken. Herbert, dank je wel voor je hulp bij het programmeren in het begin, en Wietse, dank je dat ik altijd met vragen bij je terecht kan. Eddy, ik waardeer het enorm dat je altijd een luisterend oor hebt en vertrouwt in mijn kunnen. Samen rijden met Obbe en Michelle maakte het forenzen een stuk gezelliger. Het is jammer dat het de laatste tijd lastiger werd te organiseren. Met heel veel plezier (en buikpijn) denk ik terug aan bijeenkomsten van het HighNooN project. Nies, Annemarie, Eddy, Claire, Jochen, Catharien en Christian, jullie waren een ontzetten fijn team.
Working on and with a model that is maintained at another institute requires a good cooperation with the other developers. I was very lucky in having such good colleagues at PIK in Potsdam, who were very much supporting my project. Dieter Gerten, I really appreciated our cooperation. You have always shown interest in my work, always thought along with me, and made sure that I could come to Potsdam anytime I wanted or needed it. Further, you were always the first to provide very useful comments on my manuscripts. Stefanie Rost helped me to get started with LPJmL. And Jens, I really enjoyed working with you. You have been very valuable in discussions about research ideas and I am almost embarrassed to admit that I have really good memories of the hours when we were sitting behind the screen, puzzling on the source code. Almost as good as the evenings in lively Potsdam with you and Christoph. Thanks for welcoming me.
Ingjerd Haddeland, thank you for the very helpful discussions about the implementation of the reservoir algorithm and of course for my first lessons in cross-country skiing.
Obbe en Chris, dank voor jullie vriendschap. Ik ben blij dat jullie mijn paranimfen willen zijn.
Na een dag werken is het altijd fijn thuiskomen in de Coornhertstraat, ons dorpje in Utrecht.
Er is namelijk veel meer dan werk, en ik prijs mij gelukkig met lieve vrienden, die ik vooral het laatste jaar veel te weinig heb gezien. Ik ga het goedmaken. Want jullie geven mij energie en doen mij beseffen wat echt belangrijk is. Inge en Stan, na een (kampeer)weekend met jullie kan ik er weer even tegenaan. Marieke, Jolie, Karin, Kata, Marcel, Mijke, Manon, Arvi, Monique, Liselotte, Hilde, Hanna , Bart, Rachel en anderen, dank jullie voor liefde en steun. Nadine, al sinds de brugklas ben jij er altijd en onvoorwaardelijk. En ik ben heel trots dat jij mijn boekje hebt ontworpen, het ziet er super uit!!
Het is fijn om familie te hebben waarbij je je thuis voelt: Merijn, Sanne en Jeroen, Marjolein en Rutger, Gerrit en Jeanet. Maar vooral mijn allerliefste papa en mama, dank jullie wel voor jarenlang geven van ruimte, vertrouwen en altijd voor mij klaar staan.

En dan natuurlijk tot slot, lieve Matthijs. Jij hebt het niet altijd makkelijk gehad met mij, vooral niet de afgelopen maanden. Eigenlijk ben jij een half jaar papa en mama tegelijk geweest, terwijl ik op zolder zat. Jouw eerlijkheid, nuchterheid en relativeringsvermogen werden je niet altijd in dank afgenomen, maar ik waardeer het enorm. Ik vind het fantastisch om samen met jou te genieten van onze zonnetjes Elin en Stella. Ik hou van jullie!

Curriculum Vitae

Hester Biemans was born on the 19th of August 1977 in Nijmegen, the Netherlands. After finishing secondary school in 1995 she studied Applied Physics at the University of Twente for two years. In Nijmegen she continued her studies with an MSc program in Environmental Sciences. During an internship at the National Institute for Public Health and the Environment she obtained her first experience with global scale modelling of climate impacts on food production and she developed interest in integrated assessment modelling. Hester concluded her studies with a second internship at the Centre de Recherche Public Gabriel Lippmann in Luxembourg where she implemented a hydrological model for a small subcatchment of the Rhine river basin.

After her graduation Hester worked for the department of Environmental Sciences at the University of Nijmegen, developing and coordinating study courses. She spend a year cycling through Asia, and after that became a researcher at the Netherlands Environmental Assessment Agency in 2003, where she investigated the processes leading to expansion of European cities by using urban land use change models. In 2006 Hester joined Alterra and started her PhD research at the Earth System Science and Climate Change group of Wageningen University, in close collaboration with the Netherlands Environmental Assessment Agency and the Potsdam Institute for Climate Impact Research (PIK). She finished her dissertation in June 2012.

Currently Hester works as a researcher at Alterra in Wageningen, The Netherlands.

List of peer-reviewed publications

Biemans, H., L. Speelman, F. Ludwig, E. Moors, A.J. Wiltshire, P. Kumar, D. Gerten, P. Kabat (in revision). Climate change impacts on water availability in five South Asian river basins and potential of adaptation options – a modelling study. Science of the Total Environment.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R. W. A. Hutjes, J. Heinke, W. von Bloh, and D. Gerten (2011), Impact of reservoirs on river discharge and irrigation water supply during the 20th century, Water Resour. Res., 47, W03509, doi:10.1029/2009WR008929.

Moors, E.J., A. Groot, **H. Biemans**, C. Terwisscha van Scheltinga, C. Siderius, M. Stoffel, C. Huggel, A. Wiltshire, C. Mathison, J. Ridley, D. Jacob, P. Kumar , S. Bhadwal, A. Gosain, D.N. Collins (2011). Adaptation to changing water resources of the Ganges basin in northern India. Environment and Policy.

Moors, E.J., R. Harding, **H. Biemans**, D. Collins, J. Froebrich, A. Gosain, A. Groot, J. Haerter, P. Kumar, M.L. Shrestha, F. Ludwig, A. Mishra, P.P. Sarthi, G. Rees, C. Terwisscha van Scheltinga, S. Tomar, C. Siderius, M. Stoffel, S. Werners (2011). Water Resources of the Ganga under a Changing Climate: interaction between Glaciers and Monsoon in the Himalaya. In: High mountain snow and ice hydrology (Proceedings of symposium HS1 held in Hyderabad, India, September 2009). IAHS Publ. no 332, 2011.

Gerten, D., J. Heinke, H. Hoff, **H. Biemans**, M. Fader, K. Waha (2011). Global water availability and requirements for future food production. Journal of Hydrometeorology.

Biemans, H., R.W.A. Hutjes, P. Kabat, B. Strengers, D. Gerten, S. Rost (2009). Impacts of precipitation uncertainty on discharge calculations for main river basins. Journal of Hydrometeorology.

Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

C E R T I F I C A T E

The Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment
(SENSE), declares that

Hester Biemans

born on 19 August 1977 in Nijmegen, the Netherlands

has successfully fulfilled all requirements of the
Educational Programme of SENSE.

Wageningen, 5 October 2012

the Chairman of the SENSE board

Prof. dr. Rik Leemans

the SENSE Director of Education

Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

The SENSE Research School declares that **Mrs. Hester Biemans** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 47 ECTS, including the following activities:

SENSE PhD Courses

- Environmental Research in Context
- Research Context Activity: Initiating and organizing special writing week on location for research group Earth System Science and Climate Change, Treignac, France, 1-5 October 2007
- Understanding Global Environmental Change: Processes, Compartments and Interactions
- Integrated Assessment of Global Environmental Change: Causes and Responses

Other PhD and Advanced MSc Courses

- Hydrology, Climate Change and Fluvial Systems , Utrecht University
- Programming in C
- Techniques for Writing and Presenting Scientific Papers
- PhD Competence Assessment
- Workshop on Project Management

Management and Didactic Skills Training

- Writing an NWO PhD project proposal and an NWO Postdoctoral project proposal
- Supervision of an MSc thesis

Oral Presentations

- Impacts of precipitation uncertainty on discharge calculations for main river basins. AGU Fall Meeting, 15-19 December 2008, San Fransisco
- Impacts of precipitation uncertainty on discharge calculations for main river basins…and a little more. SENSE symposium, 29 January 2009, Wageningen
- *HighNooN: adaptation to changing water resources availability in northern India.* The global dimensions of change in river basins: Threats, Linkages and Adaptation, The Global Catchment Initiative, 6-8 December 2010, Bonn
- Water constraints to future food supply and an assessment of possible solutions. World Water Week, 26-31 August 2012, Stockholm

SENSE Coordinator PhD Education and Research

Mr. Johan Feenstra

Funding

The research described in this thesis was financially supported by the Netherlands Environmental Assessment Agency and Alterra in Wageningen, mostly through a number of projects commissioned by the Dutch Ministry of Economic Affairs, Agriculture and Innovation and by the European Commission, Directorate General Research and Innovation. For details please refer to the respective chapters.

Design	Nadine van Kleef, ontwerpers om de hoek
Layout	Tina de Kleijn-Meeuwisz, Wageningen UR, Communication Services
Cover photo’s:	Planting Paddy Rice in India, McKay Savage
	Afternoon Irrigation, Todd Klassy
Chapter photo’s:	Ch 1 River close to its spring in the Himalayas, Kirgizstan, Matthijs de Groot
	Ch 2 Upstream tributary of Syr-Darya river, Kirgizstan, Matthijs de Groot
	Ch 3 Reservoir in Lesotho, Hester Biemans
	Ch 4 Afternoon Irrigation, Todd Klassy
	Ch 5 Planting paddy rice in India, McKay Savage
	Ch 6 Rice fields belonging to local hill tribes in Sapa, Viet Nam, UN Photo/ Kibae Park