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Greening the global water system

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SUMMARY

Recent developments of global models and data sets enable a new, spatially explicit and process-based assessment of green and blue water in food production and trade. An initial intercomparison of a range of different (hydrological, vegetation, crop, water resources and economic) models, confirms that green water use in global crop production is about 4–5 times greater than consumptive blue water use. Hence, the full green-to-blue spectrum of agricultural water management options needs to be used when tackling the increasing water gap in food production. The different models calculate considerable potentials for complementing the conventional approach of adding irrigation, with measures to increase water productivity, such as rainwater harvesting, supplementary irrigation, vapour shift and soil and nutrient management. Several models highlight Africa, in particular sub-Saharan Africa, as a key region for improving water productivity in agriculture, by implementing these measures.

Virtual water trade, mostly based on green water, helps to close the water gap in a number of countries. It is likely to become even more important in the future, when inequities in water availability are projected to grow, due to climate, population and other drivers of change.

Further model developments and a rigorous green–blue water model intercomparison are proposed, to improve simulations at global and regional scale and to enable tradeoff analyses for the different adaptation options.

Introduction

Out of the total precipitation over the continents, only one third becomes runoff in rivers and recharges aquifers, so-called blue water (see Box 1), which takes the liquid route to the sea. Two thirds infiltrate into the soil, forming the so-called green water (see Box 1) that supplies the plant cover, and returns to the atmosphere as vapour flow. In spite of the dominance of green water in plant production, it is still common to seek solutions to water deficits in crop production mainly by increasing irrigation, i.e. adding blue water. At the same time, soil moisture has generally been interpreted merely as a component of the soil (Falkenmark and Lundqvist, 1996). Hydrologists' interest in green water as a resource originally grew out of studies by Soviet hydrologists in the early days of the International Water Decade (1965–1974). L'vovich (1974), for instance, quantified the amount of water involved in terrestrial biomass production and developed from that comprehensive water balances for all continents and major ecological regions.

Today, the new focus on providing more water for food production for a growing population results in warnings – in particular from the ecological community – that the limits of irrigation expansion have been reached in many regions. As a result of increasing water withdrawal, primarily for agriculture, a growing number of river basins are "closing" with no uncommitted river flow left (Falkenmark and Molden, 2008). Integrated Water Resources Management (IWRM) with a focus on blue water only, can no longer provide sustainable solutions. This has generated interest in the potential of the invisible green water resource for additional crop production, and in shifting more of the green water flow from unproductive evaporation to productive transpiration. The new paradigm of managing precipitation as the key resource, including both green and blue water, provides an additional degree of freedom to help close the water gap (Falkenmark and Rockström, 2004). The integrated green–blue water approach opens up new avenues for research as well as for sustainable development and poverty alleviation.

Recent model developments enable a global, spatially explicit, consistent and process-based assessment of green and blue water availability, flow paths, and productivity, particularly in agriculture (Alcamo et al., 2007a; Liu et al., 2007; Rost et al., 2008; Vörösmarty et al., 2005). With the advanced models at hand, the full water resource, i.e. blue and green water, can be addressed, together with a

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wide range of possible interventions from soil and water conservation all the way to large-scale water infrastructure, and associated potentials for increasing food security and environmental sustainability (Rost et al., submitted for publication).

Box 1

Definition of green and blue water.

Following the definition of Rockström et al. (2009), green water is the soil water held in the unsaturated zone, formed by precipitation and available to plants, while blue water refers to liquid water in rivers, lakes, wetlands and aquifers, which can be withdrawn for irrigation and other human uses. Consistent with this definition, irrigated agriculture receives blue water (from irrigation) as well as green water (from precipitation), while rainfed agriculture only receives green water.
Rainwater harvesting, as addressed by Wisser et al. (this issue), is at the interface of blue and green water. Catching runoff and storing it in small reservoirs (or possibly underground) is interpreted as blue water management, enhancement of soil infiltration as green water management.
The papers in this special issue consistently use this resource definition, and separately calculate green and blue consumptive crop water use and green and blue virtual water content in irrigated and rainfed agriculture.

This special issue synthesises green and blue water simulations from a wide range of global models with different origins, ranging from hydrological, vegetation and crop models, to partial and general equilibrium economic models. Accordingly, the focus of the different authors varies.

Menzel and Matovelle (this issue) simulated future global and regional blue water scarcity for a range of different climate and socio-economic scenarios and the relative importance of changes in water availability versus changes in demand.

Fader et al. studied consumptive crop water use and resulting virtual water content of crops in rainfed and irrigated systems, revealing significant differences between regions and also for future climate and CO_2 scenarios.

Siebert & Döll studied crop water productivity and virtual water content of various crops, showing a large dominance of green water in average virtual water content (1100 m^3/ton) compared to blue water (291 m^3/ton). They also calculated the hypothetical loss in total cereal production if there was no irrigation (−20%).

Hanaski et al. analysed the global virtual water trade, i.e. the amount of real water demand substituted by virtual water imports, the water footprint left in the exporting countries and the global water savings from trade. They also quantified green and blue water contributions to virtual water trade as well as contributions from non-renewable sources and from medium-sized reservoirs.

Calzadilla et al. focus on the role of green and blue water in agriculture and international trade. They compared a water crisis scenario with a sustainable water use scenario, the latter eliminating groundwater overdraft and increasing allocations for the environment. They quantified the contribution of irrigation to short-term economic welfare, and the difficult tradeoffs with long-term sustainability goals in countries with groundwater overdraft, as well as knock-on effects in other countries.

The study by Sulser et al. combines blue and green water management strategies with other complementary agricultural investments. They show for different scenarios how a combined approach has the potential to positively impact the lives of many more poor people around the world.

Wisser et al. quantified the potential of different intensities of small-scale rainwater harvesting, water storage and supplemental irrigation, for increasing global cereal production, with the largest potential increases being found in Asia and Africa. They also show the potential negative impacts on downstream river flow.

Finally, Liu & Yang simulated the consumptive water use in croplands, and compared the blue water fraction with national and sub-national statistics. They show that during the growing period, the croplands globally consumed a total of 5940 km^3 $year^{-1}$ (84% of which was green water), and over the entire year 7323 km^3 $year^{-1}$ (87% green). They demonstrate the potential for better management of this resource, in particular in combination with nutrient management.

The models

All models in this special issue calculate and parameterise water-related processes differently (see below and Table 1), though some of them have for the first time been forced consistently with the same input data, which allows for an initial intercomparison of the simulated green and blue water consumption, crop water productivity, and virtual water content – see Table 2 and Fig. 1.

The biophysical models (GEPIC (Liu et al., 2007; Liu, 2009), GCWM (Siebert and Döll, 2008), H08 (Hanasaki et al., 2008a,b), LPJmL (Rost et al., 2008; Fader et al., this issue), WaterGap (Döll et al., 2003), WBM_{plus} (Wisser et al., this issue)) compute the water fluxes and related processes on a grid cell basis, at 0.5° resolution. They calculate soil water balances based on climate, land cover (cropland, pasture, natural vegetation) and soil information. Soil water content thresholds are set at which irrigation is triggered. Irrigation water demand is always met in areas equipped for irrigation, in the first place from blue water available within the respective pixel, or if that is not enough, from other sources that are not specified further, e.g. assumed fossil groundwater or transfers from other pixels. H08 includes in each pixel the capacity of medium-sized reservoirs to carry over excess water into drier periods. WBM_{plus} tests the potential for rainwater harvesting within a pixel to fulfill the irrigation water demand. GEPIC combines the modelling of hydrology, crop growth, nutrient cycling, tillage and agronomics, simulating the effects of different agricultural management options.

IMPACT (Rosegrant et al., 2008) is a partial agricultural sector equilibrium model, operating for 281 food producing units, aggregating hydrology from an underlying global hydrology model operating at 0.5°; non-irrigation blue water demands are met first and the remainder is available for irrigation, which might be met fully or partially.

Potential evapotranspiration (PET) in the biophysical models is calculated following different approaches: Penman–Monteith (GCWM), Priestley–Taylor (GCWM, IMPACT, LPJmL, WaterGap), Hargreaves (GEPIC), Hamon (WBM_{plus}), or bulk formulas (H08). The GCWM analysis shows differences of more than 20% in estimated crop blue water use, depending on the method used for determining PET, indicating the importance of model choice and the associated parameterisation (Siebert & Döll, this issue).

Some models (GEPIC, LPJmL) internally calculate crop yields, while other models (GCWM, WBM_{plus}) use (mostly country-based) crop production data from agricultural statistics. The ratio of crop yield per unit of crop water use determines the crop water productivity (CWP), or the inverse, i.e. the virtual water content (VWC). CWP and VWC are a function of various factors, such as crop type, local climate and crop management practices. Each crop type has a

Table 1
Key characteristics and input data of the global hydrological models presented in this special issue.

	H08	GEPIC	LPJmL	GCWM	WBMplus	WaterGap2	IMPACT
Spatial resolution	0.5°	0.5°	0.5°	5 min	0.5°	0.5°	281 Food producing units
Climate	NCC–NCEP–NCAR reanalysis CRU corr, Ngo-Duc et al. (2005)	CRU TS 2.1	CRU TS 2.1	CRU TS 2.1	CRU TS 2.1	CRU TS 2.1	CRU TS 2.1
Land cover (cropland)	Ramankutty et al. (2008)	Ramankutty et al. (2008)	Portmann et al. (submitted for publication)	Ramankutty et al., (2008)	Ramankutty et al. (2008)	Ramankutty et al., (2008)	Ramankutty et al. (2008)
Land cover (irrigated)	Siebert et al. (2005)	Siebert et al. (2007)	Portmann et al. (submitted for publication)	Siebert et al. (2007) and Portmann et al. (submitted for publication)	Siebert et al. (2007)	Siebert et al. (2005)	Siebert et al. (2007)
Land cover (crop type)	Monfreda et al. (2008)	22 Irrigated + 22 rainfed crop classes (acc to Ramankutty & Portmann)	Portmann et al. (submitted for publication) aggregated to 12 CFTs, separate for irrigated and rainfed land (Fader et al., this issue)	26 Irrigated + 26 rainfed crop classes	Monfreda et al. (2008) aggregated to four classes	GLCC	20 Irrigated and rainfed crops; You et al. (2006)
Soils		ISRIC – WISE (Batjes, 2006)	Eight types, based on FAO (1991) and Zobler (1986)	ISRIC-WISE (Batjes, 2006), crop specific rooting depth according to Allen et al., 1998	Digital soil map of the world (FAO/UNESCO)	FAO	Priestley–Taylor
PET	Bulk formula (Robock et al., 1995)	Based on ET_0 (for reference crop), e.g. Hargreaves and Samani, 1985	Gerten et al. (2007): Priestley–Taylor method	Penman–Monteith or Priestley–Taylor	Hamon (1963)	Priestley–Taylor	Priestley–Taylor
Reservoirs	Hanasaki et al. (2006)		Yes, unmanaged		Reservoir routing scheme, reservoirs from Vörösmarty et al. (1997)	GLWD	
Irrigation	From runoff within the same cell for plus unlimited fossil gw as required		From discharge within the same cell plus unlimited fossil groundwater and diversions as required		From runoff (or active groundwater) or RWH and small ponds, plus unlimited fossil gw as required	From runoff within the same or neighbouring cell	From basin runoff regulated by aggregated reservoir storage and constrained by surface water delivery capcity; groundwater constrained by pumping capacity.
Crop calendar		Crop calendar from FAO	Modelled sowing and harvesting dates (Bondeau et al., 2007)	Crop calendar prescribed	In irrigated areas based on climate	No	Mostly FAO CROPWAT, with some adjustments
Crop productivity	EPIC type (Krysanova et al., 2000), here using FAO yields	CWP = Y/ET (Liu et al., 2007)	Modelled dynamically (Bondeau et al., 2007)	CWP = Y/ET, average yields consistent with FAO Irrig. + rainf. yields depending on average reported yields and water stress	No	No	Irrigated and rainfed yields based on FAO reporting and You et al. (2006) and adjusted for water stress and climate effects

Table 2
Global consumptive blue and green water use in agriculture (km^3 year^{-1}).

	Blue water (irrigation)	Green water (rainfed cropland, cropping period)	Green water (rainfed and irrigated cropland, cropping period)	Green water (rainfed and irrigated cropland, full year)	Green water (rainfed and irrigated cropland, full year) plus 1/3 of grazing land water consumption
GCWM	1180–1448*	4586–4772*	5505–5731*	9823 (PM[a])	–
GEPIC	927	–	4987	6371	–
H08	1530	4700	5550	9540	13,860
IMPACT	1425	3272	4975	–	–
LPJmL	1364	5088	5469	–	+3269
WaterGap	1300	–	–	8290	11,550
WBM	1301	–	–	9406	13,819

[a] PET calculated according to Penman-Monteith.
* For different PET calculations.

specific harvestable fraction of the total plant biomass produced. Crops with a high harvestable fraction (e.g. sugarcane) have higher CWP than those with a low harvestable fraction (e.g. coffee). Moreover, the plant metabolism, i.e. C3 versus C4, also affects CWP, with C4 plants having higher CWP in a given location (Liu, 2009). LPJmL additionally simulates physiological processes with consistent water and carbon fluxes and stores in agricultural and also natural vegetation, which enables an assessment of the effects of changes in atmospheric CO_2 concentration on CWP and VWC. WaterGap also simulates in detail non-agricultural water demands and the increasing inter-sectoral competition for water.

The economic models (the partial equilibrium agricultural sector model IMPACT (Sulser et al., this issue) and the general equilibrium model GTAP-W (Calzadilla et al., this issue)), initially developed to explore the impacts of different water and food related policies, are not pixel based. Instead, they calculate green and blue water contributions to rainfed and irrigated agriculture for different geographic aggregations that are either countries, sub-regions, or some other divisions (281 food producing units for IMPACT, 16 regions for GTAP-W), as a function of food demands, supplies, prices and trade between the regions.

All of the participating models used monthly climate data from the Climate Research Unit (CRU, University of East Anglia), mostly the TS 2.1 dataset (Mitchell and Jones, 2005). Those models that simulated future crop water uses and yields under climate change (IMPACT and LPJmL) used the SRES B2 and A2 scenarios, respectively. Both of these models also simulate the combined effect of climate and CO_2 change, though in slightly different ways. IMPACT simulated agricultural production and water use also in response to changes in income, population growth, technological change and other factors according to Millennium Ecosystem Assessment (2005) and IAASTD (2008) scenarios.

Land use in all models is based on the Ramankutty et al. (2008) distribution and extent of cropland and permanent pasture, with permanent pasture being defined according to FAO as "land used permanently (5 years or more) for herbaceous forage crops, either cultivated or growing wild". Areas equipped for irrigation were taken from Siebert et al. (2007) and crop types from Monfreda et al. (2008) or Portmann et al. (2008) – the latter dataset consistently combines the distribution of irrigated and rainfed areas from Siebert et al. (2007) and Monfreda et al. (2008). While land use change is part of the IMPACT and GTAP-W and to some extent also WaterGap simulations, all other models assume no change in future land use.

Main findings

Despite major differences in model design and parameterisation and some differences in the forcing data, a number of converging messages emerged, related to the consumptive green and blue water use in agriculture. The participating models agree on (i) the dominant role that green water plays in food production, (ii) a critical overexploitation of renewable resources in many regions of the world, and (iii) the need and large potential for increasing green and/or blue crop water productivity globally.

Dominance of green water in food production

The synthesis of contributions to this special issue shows that globally, green water use by crops is about 4–5 times larger than consumptive blue water use (Table 2). Calculations of crop water use were usually limited to the cropping period – also when calculating green and blue VWC of crops. However, there is significant additional evapotranspiration (ET) for annual crops during the fallow period, which lasts about half the year on average (Siebert, pers. comm.). When including ET fluxes during the fallow period to the total consumptive crop water use, the green-to-blue ratio increases further, given that there is practically no irrigation (blue water use) during the fallow period. On top of that, the ratio shifts even further towards green water when meat and dairy production from grazing land are taken into account (Table 2).

While the models generally agree on the global numbers (1250 km^3 year^{-1} ± 25% for consumptive blue and 5250 km^3 year^{-1} ± 6% for green water use during the cropping period) they produce considerable differences in the spatio-temporal patterns of consumptive green and blue water uses in agriculture, e.g. the amounts of green water going into rainfed versus irrigated cropland, or the amount of water consumed during the cropping period versus the fallow period, and also the amount of water leaving the field as productive transpiration versus unproductive evaporation (data not shown). Despite these differences, some general patterns emerge.

Agriculture in sub-Saharan Africa, except for a few countries, depends almost completely on green water. In contrast, high blue water consumption is consistently found in semi-arid to arid countries with large areas equipped for irrigation (GEPIC, GCWM). It should be noted here, that even regions that strongly depend on irrigation, such as the MENA (Middle East – North Africa) region, meet at least half of their total crop water demand from green water, either from rainfed areas or from precipitation over irrigated land – although the blue water dependency of some countries within these regions is higher than 50%.

Green water use in agriculture is projected to grow faster over the coming decades than blue water use globally and in many regions, for several reasons (e.g. IMPACT, WaterGap (Alcamo et al., 2007a)). Initial analysis confirms this finding from a resource perspective, given that many countries which are approaching or have already reached an absolute shortage of blue water (as indicated by a threshold of 1000 m^3 capita^{-1} year^{-1} of blue water) still have a lot of potential to develop and/or improve the use of their green water resources (see Rockström et al., 2009, Falkenmark et al.,

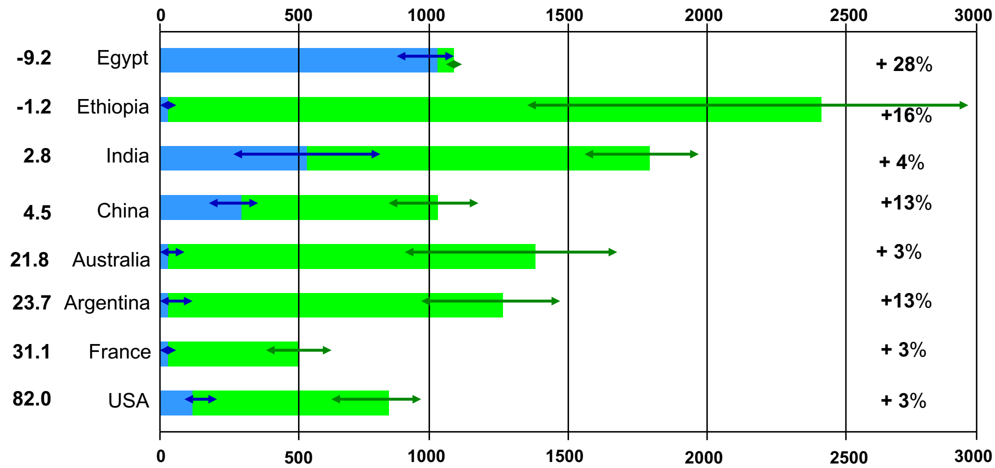

Fig. 1. Virtual water content (m^3/ton of yield) of cereals green (blue) bars show mean green (blue) virtual water contents (VWC) for the four models GCWM, GEPIC, H08 and LPJmL, green and blue arrows the spread between them. LPJmL values were only calculated for temperate cereals and maize (Ethiopia only for temperate cereals). Numbers left of the country name show net cereal trade in the year 2000 (million tons), negative numbers indicate net importers, positive numbers net exporters (from FAOSTAT). Numbers right of the bars show projected average change in VWC between now and 2041–2070, calculated with LPJml, averaged across HadCM3, ECHAM5 and CCSM3 climate simulations and with and without CO_2 effect: note, that these numbers were not taken from contributions to this special issue, but were separately provided by the authors for this synthesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2009). Additional large fluxes of green (and blue) water for bioenergy production are projected if current trends continue (Berndes, 2008). Sulser et al. (this issue) indicate an increasing biofuel feedstock demand until about 2025 and a relaxation in demand thereafter, when second and third generation biofuel technologies are expected to become available. Green and blue water requirements for second and third generation technologies are highly uncertain and therefore difficult to estimate.

Overexploitation of water resources

Many previous studies pointed out that blue water resources are, or will be, overexploited in several regions and basins (e.g. Alcamo et al., 2007a; Rosegrant et al., 2002; Smakhtin et al., 2004), as witnessed by the well-known (permanent or temporal) drying up of rivers around the world, e.g. the Nile, Yellow, Colorado or Jordan rivers. Simulations for this special issue confirm this critical overexploitation from a different perspective: current irrigation water demand for matching observed crop production in irrigated areas (as for example listed in FAO AQUASTAT (www.fao.org/nr/water/aquastat/main/index.stm), cannot be met from local, renewable water resources in a large number of pixels (indicated by GCWM, LPJmL, WBM_{plus}). An estimated 500–700 km^3 $year^{-1}$, or about 50% of the total consumptive blue water use for irrigation is non-renewable and/or cannot be covered locally (Wisser pers. comm.; see also Rost et al., 2008), which means that it has to be covered either from groundwater exploitation above the recharge rate (including fossil groundwater), from other non-conventional resources such as wastewater reuse, or from transfers from other regions. H08 results show that slightly less than half of all blue virtual water imports are based on non-renewable groundwater. IMPACT uses a different indicator to assess water demand in excess of supply, irrigation water supply reliability; simulations show that about 30% of irrigation water demand cannot be met. The Millennium Ecosystem Assessment (2005) estimated that up to 25% of current global freshwater use is maintained only through engineered water transfers and/or overabstraction of groundwater. While for sustainable management a clear distinction has to be made between water transfers and over-abstraction from non-renewable (fossil) groundwater, global models do not yet distinguish between these two different contributions to irrigation. Initial implementation of reservoir management and water transfers for irrigation is just beginning, e.g. in the H08 and LPJmL models.

The highest absolute values of non-renewable (ground-)water abstraction occur in parts of India and China and to a lesser extent in Central and West Asia, North Africa and in the Western US (WBM_{plus}, H08). These findings agree in their spatial patterns with earlier estimates of groundwater overdraft, e.g. from Kemper (2007), who quantified the combined current groundwater overdraft for India, China and the MENA region together to be in the order of 160 km^3 $year^{-1}$.

Interestingly, Calzadilla et al. (this issue), using a general equilibrium model (GTAP-W) calculate that from a strict economic perspective it would be preferable to maintain the groundwater overdraft, because total welfare is higher than in the sustainable water use scenario where the groundwater overdraft would be reduced by 190 km^3 $year^{-1}$ in 2025 compared to business as usual. However, this assessment only includes immediate agricultural benefits of groundwater use, and omits the value of ecosystem services as well as the bequest (future) value of groundwater or longer term economic losses beyond irreversible over exploitation.

Current and future water productivity/virtual water content

Generally, crop water productivity (CWP) and its inverse, virtual water content (VWC) vary significantly between regions and climates. Higher CWP is generally correlated with higher yields (see also Fader et al., this issue). The first analyses of green and blue water contributions to CWP and VWC were done only recently (Yang and Zehnder, 2007). Adding irrigation water had no marked effect on the ratio of crop yield to water consumption (LPJmL). This is basically due to the fact that when additional blue water is supplied through irrigation, more water is used per area, but at the same time the yield also increases. Hence, comparisons between irrigated and rainfed CWP/VWC, for regions with similar climate, soil and crop types, show no large differences. IMPACT estimates that crop water productivity for grains globally is about 10% higher in rainfed than in irrigated systems, due to the extensive and highly productive rainfed cereal systems in Europe and North America. In contrast, according to GCWM results, average CWP in irrigated cereal production was about 15% greater than average

CWP in rainfed cereal production (Siebert, pers. comm.). Liu et al. (2007) also found slightly higher CWP for wheat under irrigated than under rainfed conditions globally, probably due to restrictions in crop development under water limitations in rainfed agriculture.

Drier and warmer climate generally increases the amount of water required per unit of biomass produced. Improved crop and soil management, such as fertilisation, soil conservation or tillage can reduce water demand for biomass production. Accordingly, we find highest CWP/lowest VWC in parts of Europe and North America and lowest CWP/highest VWC in parts of Africa (e.g. LPJmL, GCWM, GEPIC (Liu et al., 2007)).

When projecting CWP/VWC into the future, several driving forces need to be taken into account, such as investment in agricultural water management, technological development, climate change, and increasing atmospheric CO_2 concentration. CWP is projected to increase slightly faster for rainfed cereals than for irrigated cereals under baseline conditions (IMPACT), i.e. 30% increase in CWP for rainfed versus 25% for irrigated cereals globally by 2050, under the SRES B2 scenario including CO_2 effects. This is primarily a result of new, better climate-adapted varieties and improved crop management practices. When improvements in crop management or new varieties are not taken into account, future VWC increases (or CWP decreases) in many regions in response to climate change (LPJmL), due to a combination of increasing evaporative demand with higher temperature and lower, or more irregular, precipitation and the resulting losses in yield – see Fig. 1. If the full effect of increasing atmospheric CO_2 concentration is added, the negative climate effect is more than offset, such that VWC decreases (CWP increases) in most regions of the world. This last finding should be interpreted carefully, because it assumes that there are no other limiting factors interfering, such as insufficient nutrient supply or non-optimal crop management.

Adaptation options to increasing water scarcity and for food security

Given the increasing future water demand for food (e.g. Rockström et al., 2007), but also the projected competition for water, in particular for bioenergy (Berndes, 2008), and the projected impacts from climate change (IPCC, 2007), there is an urgent need for identifying, quantifying and comparing the potential of different adaptation options, to address the increasing water scarcity and variability – individually and cumulatively. Depending on the specific conditions in a particular region, country, or basin, three major options to overcome water constraints in food production exist and have been addressed to some extent in this special issue: (i) intensification on existing agricultural land, (ii) area expansion onto non-agricultural land, (iii) virtual water trade.

Intensification on existing agricultural land

As shown by Rockström et al. (2009), many countries have considerable degrees of freedom in green and/or blue water use, to increase water productivity and food production. Better green water management in some cases may "re-open" closed basins, in which all blue water resources are already committed: if green water productivity can be improved, the need for irrigation water withdrawals may be reduced accordingly.

There are a number of options for improving management, e.g. further resource development, rainwater harvesting and storage for supplementary irrigation, crop selection, crop breeding and improved cropping practices, fertilizer, soil and water management. Hanasaki et al. (this issue) assessed the potential of medium-sized reservoirs, Wisser et al. (this issue) assessed the potential of rainwater harvesting and supplementary irrigation, and Liu & Yang (this issue) assessed the potential of improving irrigation and fertilizer status for increasing water productivity and crop production – see below for more details on these and other adaptation options.

Irrigation. One of the major adaptations to permanent or temporal water scarcity is irrigation, which increases yields and reduces the risk of crop failure. Global cereal production would be 20% lower (rice 39% lower) if no irrigation (blue) water was applied to current cropland (GCWM). Regionally this loss would be much higher, for example 66% in the MENA region. These findings are in line with those of Rost et al. (submitted for publication), who found that global crop net primary production (NPP) was increased by 17% through current irrigation. They also simulated with LPJmL the hypothetical effect of unlimited irrigation. If all current cropland was fully irrigated, total crop NPP would increase by 77%.

Hence, an important question for further water assessments is how much more blue water can sustainably be withdrawn in a particular region or basin for food production, without compromising other water demands, including environmental flow requirements? (This is in addition to the question of whether the required infrastructure can be developed for making this water available.)

Rainwater harvesting, storage and supplementary irrigation. Rainwater harvesting (RWH) in conjunction with small-scale storage and supplementary irrigation has been identified as a key adaptation option to address water scarcity (e.g. Oweis and Hachum, 2006), in particular in countries that have only limited capacity for large-scale infrastructure such as reservoirs, water transfer and irrigation systems. RWH works best under pronounced seasonality with excess water in the rainy season which can be stored. WBM_{plus} and LPJmL (Rost et al., submitted for publication) confirm this, when simulating RWH and storage potential globally. Wisser et al. (this issue) quantify the potential for RWH from non-cropland fractions (ex situ) of all grid cells that contain cropland, and the overall contribution of that harvested water to fulfilling crop water demands. They find that RWH can only close some of the widening gap between crop water demand and available resources. Globally, increases in cereal production between 10% and 20% are possible, depending on the total area from which rainwater is harvested, with highest potential for productivity increases where yields are currently low. For some regions, such as sub-Saharan Africa, yield increases of up to 100% are possible with RWH. Rost et al. (submitted for publication) used a similar approach to assess the RWH potential on cropland (in situ) with LPJmL. Globally, an increase in global agricultural NPP of 4% and 11% was found for harvesting and storing 10% and 25%, respectively, of all runoff from cropland, with above-average increases, e.g. in parts of western and southern Africa.

Improved soil and water management. Where fertilizer (and water) demands are satisfied, CWP for maize and wheat can double or even quadruple, in particular in low yielding regions in Africa (GEPIC), improving food production accordingly.

Rost et al. (submitted for publication) also tested with LPJmL the potential for vapour shift from non-productive evaporation to productive transpiration – e.g. achievable by mulching, which reduces soil evaporation. Global increases in agricultural NPP of 2% and 6% were simulated for a redirection of 10% and 25%, respectively, of evaporation to transpiration. The highest potential for vapour shift was found in semi-arid regions such as the Sahel and southern Africa.

Investment in agricultural water management. Sulser et al. (this issue) demonstrate the large potential for improving green and blue water use through targeted investments. Their Nile basin analysis for rainfed and irrigated cereals shows that under a "high-investment" scenario, an increase in yields, CWP and total production, goes along with a reduction in area expansion and consumptive water use, compared to the baseline scenario (Table 3). High investments can also improve market access.

The high-investment (baseline) scenario assumes total annual investments in rainfed and irrigated agriculture of US$0.36 (0.23) billion for agricultural research, and US$0.44 (0.19) billion for rural roads across all Nile basin countries (including non-Nile-basin parts of these countries) until 2050. Annual investment in irrigation would be almost identical in the high investment and baseline scenario: US$0.11 versus US$0.12 billion.

Moreover, under the high-investment scenario, calorie availability, a proxy for food security, would improve (by 800 kcal per capita per day in 2050 on average) in the Nile basin countries as a result of higher food production and resulting lower food prices, which would make food more affordable for the poor.

Area expansion onto non-agricultural land

Agricultural land has continuously expanded (according to FAOSTAT – http://faostat.fao.org at a rate of about 0.25% annually) in the second half of the 20th century. While the future trend cannot be predicted precisely, a similar future rate is plausible. The Comprehensive Assessment (2007) simulates average annual expansion rates of harvested area of between about 0.1% and 0.5% until 2050 for different scenarios.

In the IMPACT baseline scenario, the average annual rate for total irrigated (rainfed) harvested area is estimated to be 0.49% (0.34%) between 2000 and 2025, and 0.24% (0.13%) between 2025 and 2050. Following the definition of green water (soil water directly from precipitation, available for plant growth), any area expansion of agricultural land also increases the green water resource for food production. However, expansion has limitations, such as protection of other ecosystems (particularly remaining forest areas), climate protection, and limited blue water availability in the case of expanding irrigated land. Also, losses from degradation of existing agricultural land counteract area expansion.

Expansion of cropland onto suitable grazing land, situated somewhere between options 1 (intensification) and 2 (area expansion), also has a significant potential to increase food production and crop water productivity. However, Falkenmark et al. (2009) estimated that less than one third of the area expansion required by 2050 in poor countries (those countries that cannot afford to buy food/virtual water on the world market) can be met from current grazing land, while the remainder will have to come from other non-agricultural land. Expansion onto grazing land could also adversely affect pastoralist livelihoods and subsequently reduce diet quality for the poor.

Virtual water trade

With any trade in agricultural commodities, large amounts of virtual water are also traded. This mechanism actually improves crop water productivity globally (saving currently about 175 km^3 of consumptive crop water use per year when adding up five major crops and three major livestock products – H08), by shifting some food production from more arid to more humid countries, where CWP is higher/VWC is lower and where less irrigation (blue) water is required. More importantly however, the virtual water option provides water-poor countries with food they cannot produce domestically – if they are in the position to buy this food on the international market, if their socio-economic structure is flexible enough for this import substitution, and if the political sensitivity of giving up food self-sufficiency can be overcome. Many water-poor countries are not only short of water but also of purchasing power. By 2050 a third of the global population will live in water-scarce countries, which do not have the purchasing power to finance the required net food imports (Falkenmark et al., 2009; Yang and Zehnder, 2007).

Rost et al. (submitted for publication) have estimated with LPJmL that already today an additional 2.3 billion people would fall under the green–blue water scarcity threshold of 1300 m^3 $year^{-1}$ $capita^{-1}$, if there was no virtual water trade and countries had to rely for food supply on their domestic water resources only. In particular for some of the MENA countries, current net virtual water imports already reach or even exceed combined green and blue water use in domestic agriculture (GEPIC). Given the strong agreement among climate models on a reduction in future precipitation in the MENA region, the virtual water import option is expected to become even more important. The Comprehensive Assessment (2007) simulates in a "trade scenario" that 75% of food demand in the MENA region may have to be met by imports by 2050, assuming that the scarce water resources within this region would then be allocated to higher value uses.

Yang et al. (2006) found that agriculture in the largest food exporting countries is strongly dominated by green water, while water-scarce food importing countries have a high dependence on blue water for agricultural production. The new process-based and geographically explicit model simulations in this special issue confirm these findings – see examples provided in Fig. 1. Hanasaki et al. (this issue) further show with H08 that the largest virtual water fluxes originate from North America, that wheat is the dominant crop traded and that rice has the highest blue water fraction of those crops analysed (43%). Using the GTAP-W model, Calzadilla et al. (this issue) show that restrictions on groundwater use in one region (e.g. India) lead (via shifts in international food trade) to an increase of water use in other, unconstrained regions (e.g. Canada).

Note that the relative contributions of green and blue water to total yield do not allow calculations of individual green or blue water productivities. The yield responses of adding blue (irrigation) water may be highly non-linear.

Green and blue water use and potential in Africa

The contributions to this special issue suggest that global simulation results need to be analysed in more detail for differences between and within regions, and should eventually be combined with local and meso-scale information. Here we take a first look at Africa – again with only limited harmonisation among the different models.

North Africa is the most blue-water-dependent of all world regions, with more than 50% of consumptive crop water use being blue water (GCWM). Egypt has the highest fraction of blue water use (89%) of all countries (GEPIC, see also Fig. 1). Sub-Saharan Africa on the other hand is the most green-water-dependent region (e.g. in western Africa only 1.1% of consumptive crop water use is blue (GCWM)). The Nile basin, which stretches across both of these extreme regions, reflects this by having an average blue water fraction of total crop water use that matches the world average: 17% (GEPIC).

Table 3
Baseline versus high-investment scenario, for rainfed cereals in the Nile basin in 2050, according to Sulser et al. (IMPACT).

Scenario	Rainfed crop area (1000 ha)	Rainfed green water use (km^3)	Rainfed yield (ton/ha)	Rainfed green CWP ($kg\ m^{-3}$)	Rainfed production (1000 ton)
Baseline	13.04	78.14	1.64	0.27	21.41
High investment	12.12	72.47	2.06	0.35	24.96

The dominance of green water in food production in sub-Saharan Africa is expected to persist: WaterGap (based on IMPACT food production scenarios) projects a 60% increase in agricultural green water use by 2050, while consumptive blue water use in agriculture is projected to increase by only 14% (Alcamo et al., 2007b). For the Nile basin an increase in green water use by 103% and consumptive blue water use by 29% is projected for 2050 (IMPACT).

According to WaterGap simulations, domestic and industrial (blue) water demands in the Nile basin will increase by a factor of 5–20 up to 2050 (Menzel, pers. comm.). Water stress will increase accordingly. For the White Nile basin, WaterGap simulates a change from low to severe blue water stress under all climate and socio-economic scenarios (this issue). Given these future trends on top of the high current level of competition for (blue) water among the riparian countries of the Nile, green water options need to receive additional attention and investments.

Africa, in particular sub-Saharan Africa is hampered by both low agricultural productivity and low CWP (Comprehensive Assessment, 2007). Africa has the lowest rainfed cereal yields, and together with Asia also the lowest irrigated cereal yields. Eastern Africa has the lowest irrigated yield of any world region (GCWM). Rainfed CWP in the Nile basin is currently less than half of the world average and this is not expected to change over the coming decades (IMPACT). Climate change is often considered to impact food production in sub-Saharan Africa negatively (IPCC, 2008). But when the (uncertain) effect of increasing CO_2 concentrations are taken into account, crop production and CWP may actually improve (GEPIC, LPJmL). In particular yields for tropical crops, such as millet, are projected to increase across sub-Saharan Africa, except for the semi-arid to arid Sahel region (Liu et al., 2008).

All Nile basin countries are currently net importers of food and virtual water (GEPIC, IMPACT) and these net imports are projected to increase significantly by 2050 for most of these countries (IMPACT). Economies in sub-Saharan Africa, on average, will continue to grow below the average for all developing countries, according to the IMPACT baseline scenario. Therefore, the "economic water scarcity" (Comprehensive Assessment, 2007), where only about 5% of renewable blue water resources in Africa are exploited due to economic constraints, is likely to persist. Multilateral development banks and other donors have pledged to significantly expand irrigation development in the region, but given the low level of existing irrigation (only 3.5% of cultivated area is irrigated), even a doubling or tripling will still leave most farmers dependent on rainfed agriculture.

Rockström et al. (2009) showed that there is enormous potential for improving green water use in food production in sub-Saharan Africa (and also in other regions). GEPIC shows that Africa has the largest potential for improving CWP (by a factor of 2 or more), if better nitrogen management can be achieved. IMPACT scenarios demonstrate that under a "high agricultural investment" scenario, rainfed CWP could increase about twice as fast in Africa as it would globally – starting however from a much lower current level.

Hence, food security in Africa critically hinges on investments in agricultural water management, with an emphasis on locally adapted green water measures. WBM_{plus} scenarios show that Africa has the largest relative potential for increasing crop production (by about 100%) through a combination of RWH, small reservoirs and supplementary irrigation. Rost et al. (submitted for publication) showed that Africa has a larger potential for vapour shift from non-productive evaporation to productive transpiration in agriculture than most other regions, if crop and soil management was improved.

Discussion

Typically, discussions on Integrated Water Resources Management (IWRM) or Agricultural Water Management are focussed on blue water and irrigation infrastructure. Given the increasing overexploitation or other limitations of blue water resources in many regions, green water management deserves more attention and scenarios need to address the full green-to-blue (and virtual) water spectrum. This special issue synthesizes available results on green and blue water contributions to food production (see Table 2) and to trade (see Fig. 1) and potential adaptation options (see Table 4), based on a set of different global simulation models.

Note that the adaptation potentials presented in Table 4 are not directly comparable, because they were derived with different models, using different assumptions. Also, the numbers cannot be added up to derive the total potential of combinations of measures.

Furthermore these global numbers need "ground-truthing". While the results presented in this special issue provide new green–blue water information with converging messages, also on critical hotspots and most promising regions for different adaptation options, more detailed information is required for understanding local potentials and tradeoffs.

Table 4
Adaptation potentials and constraints for increasing global food production.

Adaptation option	Potential increase in global food production	Priority regions for implementation	Tradeoffs
Irrigation	20% Increase with current level of irrigation, additional 75% if all cropland was fully irrigated (LPJmL)	Basins with low water withdrawal-to-availability ratio, e.g. in sub-Saharan Africa or Latin America (WaterGap)	Competition with other water uses including environmental flows, costs of irrigation infrastructure
Rainwater harvesting/ supplementary irrigation	15% For medium intensity water harvesting from land adjacent to cropland (WBM_{plus}), 12% when harvesting 25% of all runoff from cropland (LPJmL)	Regions with high rainfall variability and excess runoff, in particular semi-arid to sub-humid sub-Saharan Africa and Latin America	Reduction in downstream water availability up to 80%, losses from storage ponds (20% of their storage capacity per year – WBM_{plus})
Vapour shifts from non-productive evaporation to productive transpiration	6% When reducing total evaporation from cropland by 25% (LPJmL)	Semi-arid regions, such as Sahel, southern Africa or central Asia	Material for mulching may be required for other purposes
Nutrient management	Doubling of crop water productivity in nutrient depleted regions (GEPIC)	Nutrient depleted and low yielding regions, in particular in Africa	Costs of fertilizer
Virtual water imports	Currently replacing more than 720 $km^3\ year^{-1}$ of local water consumption, and globally saving more than 175 $km^3\ year^{-1}$ (H08) and lifting more than 2 billion people out of green–blue water scarcity (LPJmL)	Water scarce, economically strong countries	Costs of imports, loss of rural employment and livelihoods, politically sensitive
Agricultural area expansion	Depending on restrictions imposed	Regions with suitable, non-protected land	Losses in biodiversity and other ecosystem services, carbon emissions

Only when combining the information from global models with results from meso-scale models, field experiments and other local information, it will become relevant for improved agricultural water management and related investments at national or sub-national level. For example, the global model results on rainwater harvesting and vapour shifts presented here, need to be combined with place-based information on local conditions (topography, soils, farming systems, etc.) and adoption potentials, before they can support decision making.

But also the global models themselves are to be improved, in terms of resolving spatio-temporal variability, process representation, and integration of socio-economic aspects. In particular the following aspects deserve attention in further model development:

- more realistic quantifications of consumptive blue/irrigation water use, based on separate simulation of rainfed and irrigated green and blue crop water productivity,
- improved parameterisation of yield losses from dryspells and droughts as well as yield and water productivity responses to (supplementary) irrigation and other water management options,
- better definition of the different sources of irrigation water, including fossil and renewable groundwater, wastewater reuse but also water storage, reservoir management and water transfers within and between basins,
- integration of environmental flow requirements (and water requirements of terrestrial ecosystems) and
- integration of economic and technological development scenarios, water demands, land use and land degradation.

Note, that several of these aspects have already been addressed in some of the models. Also, it should be clear from this special issue, that each of the models was developed with a different objective, addressing only some specific aspects of the global water system. There is no need for all models to address all of the above challenges, and in fact the variety of modelling approaches is to be maintained. A lot of new knowledge can already be gained from a more rigorous intercomparison of the existing models.

With further improvements, also the challenge of deriving a meaningful water scarcity index for the full green–blue water resource can be tackled. The initial green–blue water scarcity index described by Rockström et al. (2009) needs to be further developed in terms of spatio-temporal resolution of green and blue water availability (e.g. taking into account the distance of people from the source, the green water contributions from grazing land, and the virtual water contributions from trade), productivity (e.g. under different climates and agricultural management regimes), and demands (e.g. depending on diets).

Conclusions

The objective of this special issue, with its synthesis and initial comparison of different global modelling approaches, is to focus attention on green water in food production and trade. At the same time it also attempts to resolve the emerging green–blue water dichotomy, by showing the interlinkages of land and water management and the need for an integrated framework along the green–blue water continuum from rainfed agriculture and supplementary irrigation, to green water in irrigated areas to full blue water irrigation.

While higher water productivity in food production will remain a key challenge, integration has to move beyond agriculture, addressing other green and blue water uses, such as livestock and fisheries (some progress has been made in the Challenge Programme on Water and Food – www.waterforfood.org) and bioenergy, but also for a wider range of ecosystem services. The green–blue water approach can eventually serve to assess future water-related carrying capacities, globally and also for individual regions and basins.

A concerted effort across scales (from the field up to basins and regions) will be required to address and quantify tradeoffs between different green and blue water options. Some initial examples of tradeoffs are presented in this special issue.

Wisser et al. quantify the potential yield increases from rainwater harvesting and also resulting reductions in downstream runoff. But the resulting losses in food production from that reduction in downstream blue water availability have not been assessed, let alone compared to the upstream gains, yet.

Calzadilla et al. quantify the tradeoffs in economic welfare for continued groundwater overexploitation for irrigation versus additional water allocations to the environment. But the resulting environmental (potentially irreversible) damages from groundwater overexploitation and subsequent losses in ecosystem services have not been assessed yet.

Hanasaki et al. quantify environmental flow requirements, but they have not been taken into account as constraints in future irrigation scenarios yet.

Also, the potential for expanding cropland onto current grazing land is briefly addressed, but the resulting tradeoffs e.g. in terms of local livelihoods have not been assessed in any detail.

A next step beyond this special issue is now underway: a systematic intercomparison of the models presented here, using a common simulation protocol, with harmonised input data and scenario assumptions. Different parameterizations of processes such as evapotranspiration, crop production and management practices will be compared. More detailed regional analyses than presented in this special issue will also better explain differences between the models. This green–blue water model intercomparison is closely coordinated with the Water Model Intercomparison of the EU WATCH project (www.eu-watch.org) and the Global Water System Project (www.gwsp.org). It is expected to result in improvements across models, building on the respective strengths of each participating model. Jointly, the suit of models can move scientific understanding of the global water system to a new level, and generate new knowledge for enhancing water and food security.

References

Alcamo, J., Floerke, M., Maerker, M., 2007a. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrological Sciences 52 (2), 247–275.

Alcamo, J., Weiss, M., Schaldach, R., Voss, F., You, L., 2007. Future cropland in Africa: the outlook for green and blue water fluxes. In: GWSP Issues in Global Water System Research No. 2, Global Assessments: Bridging Scales and Linking to Policy.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evaporation: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organisation of the United Nation (FAO), Rome.

Batjes, N.H., 2006. ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes grid. Report 2006/02, ISRIC – World Soil Information, Wageningen.

Berndes, G., 2008. Future biomass energy supply: the consumptive water use perspective. Water Resources Development 24 (2), 235–245.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Mueller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13, 128.

Calzadilla, A., Rehdanz, K., Tol, R., this issue. The economic impact of more sustainable water use in agriculture: a computable general equilibrium analysis. Journal of Hydrology.

Comprehensive Assessment, 2007. Comprehensive Assessment of Water Management in Agriculture, Water for Food, Water for Life. Earthscan, London.

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

Fader, M., Gerten, D., Müller, C., Rost, S., this issue. Virtual water content of temperate cereals and maize: Present and potential future patterns. Journal of Hydrology.

Falkenmark, M., Lundqvist, J., 1996. Comprehensive water resources assessment. In: UN Comprehensive Assessment of the Freshwater Resources of the World. Stockholm Environment Institute.

Falkenmark, M., Molden, D., 2008. Wake up to realities of river basin closure. Water Resources Development 24 (2), 201–215.

Falkenmark, M., Rockström, J., 2004. Balancing Water for Humans and Nature a New Approach to Ecohydrology. Earthscan, London.

Falkenmark, M., Rockström, J., Karlberg, L., 2009. Present and future water requirements for feeding humanity. Food Security 1, 59–69.

FAO (Food and Agriculture Organization), 1991. The Digitized Soil Map of the World (Release 1.0). FAO, Rome.

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

Hamon, W.R., 1963. Computation of direct runoff amounts from storm rainfall. International Association of Science Hydrological Publication 63, 52–62.

Hanasaki, N., Kanae, S., Oki, T., 2006. A reservoir operation scheme for global river routing models. Journal of Hydrology 327 (1–2), 22–41.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shen, Y., Tanaka, K., 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 (4), 1007–1025.

Hanasaki, N., Kanae, S., Oki, T., Shirakawa, N., 2008b. An integrated model for the assessment of global water resources – part 2: applications and assessments. Hydrology and Earth System Sciences 12 (4), 1027–1037.

Hanasaki, N., Inuzuka, T., Kanae, S., Oki, T., this issue. An estimation of global external water footprint and their sources of water withdrawal. Journal of Hydrology.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1, 96–99.

IAASTD, 2008. International Assessment of Agricultural Science and Technology for Development. Island Press, Washington, DC.

IPCC, 2007. Climate Change 2007 – Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, Geneva.

Kemper, K.E., 2007. Instruments and institutions for groundwater management. In: Giordano, M., Villholth, K.G. (Eds.), The Agricultural Groundwater Revolution: Opportunities and Threats to Development. Cabi Publishers.

Krysanova, V., Wechsung, F., Arnold, J., Srinivasan, R., Williams, J., 2000. SWIM (Soil and Water Integrated Model) User Manual. Potsdam Institute for Climate Impact Research.

Liu, J., 2009. A GIS-based tool for modelling large-scale crop–water relations. Environmental Modelling and Software 24, 411–422.

Liu J, Yang, H., this issue. Spatially explicit assessment of global green and blue water uses in cropland. Journal of Hydrology.

Liu, J., Williams, Jimmy R., Zehnder, A.J.B., Yang, H., 2007. GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems 94 (2), 478–493.

Liu, J., Fritz, S., van Wesenbeeck, C.F.A., Fuchs, M., Obersteiner, M., Yang, H., 2008. A spatially explicit assessment of current and future hotspots of hunger in sub-Saharan Africa in the context of global change. Global and Planetary Change 64 (3–4), 222–235.

L'vovich, M.I., 1974. World Water Resources and Their Future. Mysl, PH, Moscow.

Menzel, L., Matovelle, A., this issue. Current state and future development of blue water availability and blue water demand: a view at seven case studies. Journal of Hydrology.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Current State and Trends. World Resources Institute, Island Press.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high resolution grids. International Journal of Climatology 25 (6), 693–712. doi:10.1002/joc.1181.

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet. Part 2: the geographic distribution of crop areas and yields in the year 2000. Global Biogeochemical Cycles. doi:10.1029/2007GB002947.

Ngo-Duc, T., Polcher, J., Laval, K., 2005. A 53-year forcing data set for land surface models. Journal of Geophysical Research – Atmospheres 110 (D6).

Oweis, T., Hachum, A., 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agricultural Water Management 80 (1–3), 57–73.

Portmann, F., Siebert, S., Bauer, C., Döll, P., 2008. Global data set of monthly growing areas of 26 irrigated crops. Frankfurt Hydrology Paper 06. University of Frankfurt, Germany.

Portmann, F.T., Siebert, S., Döll, P., 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, GB1011, doi:10.1029/2008GB003435.

Ramankutty, N., Evan, A., Monfreda, C., Foley, J.A., 2008. Farming the planet. Global Biogeochemical Cycles. doi:10.1029/2007GB002952.

Robock, A., Vinnikov, K.Y., Schlosser, C.A., Speranskaya, N.A., Xue, Y.K., 1995. Use of midlatitude soil-moisture and meteorological observations to validate soil-moisture simulations with biosphere and bucket models. Journal of Climate 8 (1), 15–35.

Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. PNAS 104, 6253–6260.

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., Gerten, D., 2009. Future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resources Research.

Rosegrant, M.W., Cai, X., Cline, S.A., 2002. World Water and Food to 2025: Dealing With Scarcity. International Food Policy Research Institute and Internal Water Management Institute, Washington, DC and Colombo, Sri Lanka.

Rosegrant, M.W., Msangi, S., Ringler, C., Sulser, T.B., Zhu, T., Cline, S.A., 2008. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute, Washington, DC. <http://www.ifpri.org/themes/impact/impactwater.pdf>.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resources Research 44, W09405. doi:10.1029/2007WR006331.

Rost, S., Gerten, D., Hoff, H., Lucht, W., Falkenmark, M., Rockström, J., submitted for publication. Global potential to increase crop production through water management in rainfed agriculture. Environmental Research Letters.

Siebert, S., Döll, P., 2008. The Global Crop Water Model (GCWM): Documentation and First Results for Irrigated Crops. Frankfurt Hydrology Paper 07. Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany.

Siebert, S., Döll, P., this issue. Quantifying blue and green water uses and virtual water contents in global crop production as well as potential production losses without irrigation. Journal of Hydrology.

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

Siebert, S., Döll, P., Feick, S., Hoogeveen, J., Frenken, K., 2007. Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany/Food and Agriculture Organization of the United Nations, Rome, Italy.

Smakhtin, V., Revenga, C., Döll, P., 2004. A pilot assessment of environmental water requirements and scarcity. Water International 29 (3), 307–317.

Sulser, T.B., Ringler, C., Zhu, T., Msangi, S., Bryan, E., Rosegrant, M.W., this issue. Green and blue water accounting in the Ganges and Nile basins: implications for food and agricultural policy. Journal of Hydrology.

Vörösmarty, C.J., Sharma, K.P., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., Lough, J.A., 1997. The storage and aging of continental runoff in large reservoir systems of the world. Ambio 26 (4), 210–219.

Vörösmarty, C., Douglas, E.M., Green, P.A., Revenga, C., 2005. Geospatial indicators of emerging water stress: an application to Africa. Ambio 34 (3), 230–236.

Wisser, D., Frolking, S., Douglas, E.M., Fekete, B.M., Schumann, A.H., Vörösmarty, C.J., this issue. Blue and green water: the significance of local water resources captured in small reservoirs for crop production. Journal of Hydrology.

Yang, H., Zehnder, A., 2007. "Virtual water": an unfolding concept in integrated water resources management. Water Resources Research 43. doi:10.1029/2007WR006048.

Yang, H., Wang, L., Abbaspour, K.C., Zehnder, A.J.B., 2006. Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrology and Earth System Sciences 10, 443–445.

You, L., Wood, S., Wood-Sichra, U., 2006. Generating global crop distribution maps: from census to grid. In: Selected paper at IAAE 2006, Conference at Brisbane, Australia.

Zobler, L., 1986. A world soil file for global climate modelling. NASA Technical Memorandum, 87802.