Agricultural green and blue water consumption and its influence on the global water system

Stefanie Rost,1 Dieter Gerten,1 Alberte Bondeau,1 Wolfgang Lucht,1 Janine Rohwer,1 and Sibyll Schaphoff1

Received 9 July 2007; revised 27 May 2008; accepted 12 June 2008; published 4 September 2008.

This study quantifies, spatially explicitly and in a consistent modeling framework (Lund-Potsdam-Jena managed Land), the global consumption of both “blue” water (withdrawn for irrigation from rivers, lakes and aquifers) and “green” water (precipitation) by rainfed and irrigated agriculture and by nonagricultural terrestrial ecosystems. In addition, the individual effects of human-induced land cover change and irrigation were quantified to assess the overall hydrological impact of global agriculture in the past century. The contributions to irrigation of nonrenewable (fossil groundwater) and nonlocal blue water (e.g., from diverted rivers) were derived from the difference between a simulation in which these resources were implicitly considered (IPOT) and a simulation in which they were neglected (ILIM). We found that global cropland consumed >7200 km3 year−1 of green water in 1971–2000, representing 92% (ILIM) and 85% (IPOT), respectively, of total crop water consumption. Even on irrigated cropland, 35% (ILIM) and 20% (IPOT) of water consumption consisted of green water. An additional 8155 km3 year−1 of green water was consumed on grazing land; a further ~44,700 km3 year−1 sustained the ecosystems. Blue water consumption predominated only in intensively irrigated regions and was estimated at 636 km3 year−1 (ILIM) and 1364 km3 year−1 (IPOT) globally, suggesting that presently almost half of the irrigation water stemmed from nonrenewable and nonlocal sources. Land cover conversion reduced global evapotranspiration by 2.8% and increased discharge by 5.0% (1764 km3 year−1), whereas irrigation increased evapotranspiration by up to 1.9% and decreased discharge by 0.5% at least (IPOT, 1971–2000). The diverse water fluxes displayed considerable interannual and interdecadal variability due to climatic variations and the progressive increase of the global area under cultivation and irrigation.


1. Introduction

[2] Humans are perturbing the terrestrial water cycle at an unprecedented rate, both directly e.g., through diversions and withdrawals of water for agricultural, industrial and domestic use, and indirectly e.g., through land cover conversions and anthropogenic climate change [L’vovich et al., 1990; Vörösmarty and Sahagian, 2000; Kabat et al., 2004]. The largest portion of human “blue” water withdrawal and water consumption (withdrawal minus return flow to the river system) from rivers, lakes and aquifers is for the purpose of irrigation. Irrigation water use has been estimated to reach ~2,500 km3 year−1 globally, which represents almost 70% of total human blue water use. Global agricultural blue water consumption, i.e., the amount of water that transpires productively through the crops or evaporates unproductively from soils, water bodies and vegetation canopies, amounts to ~90% of overall blue water consumption, equaling about 1,200–1,800 km3 year−1 [Shiklomanov and Rodda, 2003; Vörösmarty et al., 2005]. As discussed by Vörösmarty et al. [2005], the amount of nonrenewable water or water transported from distant regions involved in irrigation - i.e., the amount of water withdrawn and consumed in excess of locally accessible, surface-near supplies - is highly uncertain, thus it is crucial to quantify not only the overall amount of water extraction and consumption but also the nonrenewable and allochthonous fractions within a common, consistent framework.

[3] It is a misconception, though, to regard agricultural water consumption as being dependent primarily on these blue water withdrawals. In fact, 80% of global cropland is rainfed, and 60–70% of the world’s food is produced on rainfed land, that is, by consumption of precipitation water infiltrated into the soil (so-called “green water”) [Falkenmark and Rockström, 2004]. In some regions, food production almost entirely depends on green water (>95% in sub-Saharan Africa [Alexandratos, 1995]). Green water is also important on irrigated land, as blue water is supplied there only to the amount that precipitation water is not sufficient for ensuring optimal crop growth. Hence global agricultural
water consumption is much higher than suggested by the above figures that refer to blue water only.

According to Rockström et al. [1999] and Falkenmark and Rockström [2004], the average annual green water consumption on rainfed and irrigated cropland is in the order of 5,000 km³ year⁻¹ globally, which is more than three times the blue water consumption. The apparent dominance of green water in agriculture becomes even more striking if water requirements for grazing land are included, which may amount to ~20,000 km³ year⁻¹ depending on the grassland area considered as managed [Falkenmark and Rockström, 2004]. It has also to be recognized that green water sustains all terrestrial nonagricultural ecosystems; the related water consumption has been estimated to range between 49,000 and 56,500 km³ year⁻¹ [Rockström et al., 1999; Rockström and Gordon, 2001; Falkenmark and Rockström, 2004].

While global blue water resources and consumption have been quantified comprehensively on the basis of statistical information [e.g., Shiklomanov and Rodda, 2003] and/or macroscale hydrological models [e.g., Arnell, 1999; Alcamo et al., 2000; Vörösmarty et al., 2000; Döll et al., 2003], green water consumption and its temporal variability has, despite its importance, not been the focus in global water resources assessments. Initial estimates of blue and green water consumption by L’vovich et al. [1990], Postel [1998] and Rockström and Gordon [2001] are rather crude, based on compilations of diverse static and potentially inconsistent maps of vegetation distribution, average crop productivities and yields, and average evapotranspiration rates. While those values represent more or less valid long-term global means, they do not reveal the spatial and temporal patterns of the diverse water fluxes. Other studies have focused on evapotranspiration [e.g., Dirmeyer et al., 2006; Tett et al., 2007], but they did not distinguish between evapotranspiration from natural ecosystems and that from cropland nor did they distinguish the green and blue fractions.

Furthermore, while the influences of either anthropogenic land cover change or irrigation on evapotranspiration and discharge have been quantified in previous studies [e.g., Boucher et al., 2004; Tett et al., 2007] their individual and joint influences have not yet been explicitly distinguished and quantified within a consistent framework (but see Gordon et al. [2005] or Haddeland et al. [2007], who found that the effects of these processes on evapotranspiration tend to cancel each other out globally and at continental scale).

For this study, we used an enhanced version (LPJmL_v3.2) of a well-established dynamic global vegetation and water balance model [Bonadiman et al., 2007] to quantify the historic and contemporary green and blue water consumption in global irrigated and rainfed agriculture, and the green water consumption to sustain natural terrestrial ecosystems. In addition, we quantified the extent to which anthropogenic land cover change and irrigation have affected the 20th century terrestrial water balance. The principal suitability of the model for assessing water requirements of natural and agricultural vegetation as well as green and blue water fluxes has been demonstrated earlier [Gerten et al., 2004a, 2005; Bonadiman et al., 2007].

Guiding research questions were as follows. (1) How much green water is consumed globally, differentiated between rainfed agriculture, irrigated agriculture, and natural terrestrial ecosystems? (2) How does this relate to blue water consumption? (3) How much blue water stems from nonrenewable water and from distant resources? (4) What is the spatial and temporal variability of these flows? (5) How large was the effect of human land cover change and irrigation on green and blue water flows? To address these questions, we performed several simulations for the 20th century, in which green and blue water consumption were distinguished and the individual influences of land cover change, irrigation, and nonrenewable/nonlocal blue water resources separated.

2. Methods

2.1. The LPJmL Model

The dynamic global vegetation and water balance model LPJmL (Lund-Potsdam-Jena managed Land [Bonadiman et al., 2007]) is based on LPJ [Sitch et al., 2003], a dynamic global vegetation model that computes the establishment, growth and productivity of the world’s major natural and agricultural plant types and the associated carbon and water fluxes as well as their spatiotemporal variations in response to climatic conditions and human interferences such as irrigation, typically on a 0.5° grid and at daily time steps. Natural vegetation is represented by nine plant functional types (PFTs) and agricultural vegetation by 12 crop functional types (CFTs) representing field crops as well as pasture. Agricultural vegetation can be either rainfed or irrigated (see Appendix A1 for more information).

LPJ/LPJmL model results have been extensively validated against small- and large-scale biophysical and biogeographical observations including leaf phenology, CO₂ fluxes, and crop yields [e.g., Lucht et al., 2002; Sitch et al., 2003; Bonadiman et al., 2007]. Observed soil moisture, runoff and evapotranspiration are reproduced well, and the model performs on the level of stand-alone global hydrological models [Wagner et al., 2003; Gerten et al., 2004b; Gordon et al., 2004]. As LPJmL simulates the terrestrial water balance realistically and in coupling with the dynamics of natural and agricultural vegetation, it is well suited for assessing global green and blue water fluxes, and their interannual variations, in a consistent and process-based manner.

In the model, precipitation P and irrigation water Irr are partitioned into soil moisture W, transpiration Eₚ, soil evaporation Eₛ, interception Eₛ, and runoff R (see Appendix A2 for general water balance and Appendix A7 for abbreviations). Productive water consumption Eₚ is calculated for each CFT and PFT as a function of soil water supply and atmospheric demand (see Appendix A3 for calculations). Unproductive water consumption consists of interception loss Eₛ and evaporation from soil Eₛ, lakes Eₛ and canals Eₛ (see Appendix A4). These fluxes are calculated for the different rainfed and irrigated CFTs as well as for PFTs, and distinguished by the contributions of blue (irrigation) and green (precipitation) water.

Blue water consumption is defined herein as the amount of productively or unproductively evapotranspiring water originating, e.g., from river segments, aquifers, lakes
and reservoirs, as opposed to the “green” part of soil water that originates directly from $P$. To compute the blue water stocks and flows, the existing LPJmL model was enhanced by a river routing module to calculate river discharge $Q$; lakes and reservoirs as additional water stores; and a module to consider domestic, industrial and livestock water consumption (see Figures 1 and 2a; Appendix A5).

[13] Net irrigation water requirements $NIR$ were determined from the soil water deficit below optimal growth of the present CFTs. To account for water losses on the way to the plant, gross irrigation requirements $GIR$ were computed as the quotient of $NIR$ and a country-specific irrigation efficiency $e_p$ (see Figure 2b, Appendix A5.4). We adopted two alternative approaches for estimating the amount of blue irrigation water that can be withdrawn and brought to the field. In the potential irrigation simulation IPOT irrigated crops do not experience water stress, and the water withdrawal $W_d$ equals GIR. If irrigation demand exceeds the local renewable water resource, we assume that the remaining water is withdrawn from somewhere else (e.g., fossil groundwater, desalination plants, rivers, diversions). In contrast, in the limited irrigation simulation ILIM $W_d$ is restricted by the available water in rivers, lakes, reservoirs, and renewable groundwater (see Appendix A5.5 for details).

[14] On irrigated areas, part of the water used by crops is blue by origin while another part is green by origin. To quantify the individual fractions of consumed green and blue water, a method was developed to separate these water flows (Figure 1, Appendix A6). Thus total blue water consumption $B$ was considered the sum of $E_T$, $E_S$, $E_I$ and $E_C$ of irrigation water. $B$ was counted during the growing (irrigation) period and after harvest until used up from the soil. Total green water consumption $G$ was determined as the sum of $E_T$, $E_S$ and $E_I$ of precipitation. $G$ was calculated as daily sum of all CFTs and then summed up over a whole year, that is, unproductive evaporation and interception from grasses (PFTs) that established on the fallow land outside of the CFTs’ growing periods were accounted for (Appendix A6).

2.2. Simulation Protocol

[15] LPJmL was run for the period 1901–2003, preceded by a 990-year spinup period during which the climate of the years 1901–1930 was repeated to bring PFT distribution and carbon pools into equilibrium. Climate forcing data (monthly mean temperature, precipitation, number of wet days, and cloud cover) were taken from a homogenized and extended CRU TS2.1 global climate data set [Osterle et al., 2003; Mitchell and Jones, 2005]. To estimate the uncertainty of our results that may arise from uncertainties in precipitation input, we additionally used three other precipitation data sets (see below). To get quasi-daily values, the monthly values of temperature and cloud cover were linearly interpolated; daily precipitation and the distribution of wet days were inferred using a stochastic method [Gerten et al., 2004b].
were taken from Keeling and Whorf [2005] and Sitch et al. [2003]. Soil information was derived from the FAO global database [FAO, 1991] (see details in Sitch et al. [2003]). Annual fractional coverage with cropland was prescribed by a 0.5° resolution data set for the period 1901–1992 [Ramankutty and Foley, 1999]; thereafter, it was assumed to follow the trend of the last 20 years of that period. The distribution of crop types within every cell was derived from Leff et al. [2004] for 1990. The fraction of grazing land was approximated from the HYDE data set [Klein Goldewijk and Battjes, 1997] for 1970. For the entire period we derived the annual distribution of the different crops and grazing land by assuming no temporal change of their relative distribution. To assign irrigated cropland and pasture land we used a map of areas equipped for irrigation around the year 2000 (see Figure 2a for distribution [Siebert et al., 2007]); the cells’ cropland and pasture fractions that could be irrigated according to this map were assumed to be constant over the entire time period. In 1901 we assumed only rice to be irrigated. We used data on efficiencies for irrigation prepared by Rohwer et al. [2007] (Figure 2b, Appendix A5.4). The river network topology was derived from the global 0.5° drainage direction map DDM30 of Döll and Lehner [2002]. To derive for each grid cell the area occupied by lakes and reservoirs we used the global database of Lehner and Döll [2004]. Water consumption by households, industries and livestock was derived from Alcamo et al. [2003a] (see Appendix A5.3).

Four simulations were performed: (1) A model run taking account of both PFTs and CFTs, assuming irrigation water withdrawal to be constrained by local, renewable water storages (S, equation A7) (ILIM simulation); (2) same as (1) but assuming sufficient water storage to fulfill GIR (IPOT simulation); (3) same as (1) but without irrigation (INO simulation) in order to assess the impact of irrigation on the terrestrial water balance; and (4) a model run for potential natural vegetation only, i.e., without cropland and pastures (PNV simulation), to assess the hydrologic impact of human land cover and land use change.

Figure 2. (a) LPJmL-simulated average river discharge for the period 1971–2000 (km³ year⁻¹, grey) and percentage area of 0.5° grid cells equipped for irrigation around the year 2000 (colored after Siebert et al. [2007]). (b) Country-scale irrigation project efficiencies eP (after Rohwer et al., 2007), plotted for the areas equipped for irrigation.
Table 1. Estimates (km$^3$ yr$^{-1}$) of Green (G) and Blue Water Consumption ($B$), Differentiated Between Natural Ecosystems (PFTs), Lakes and Reservoirs ($E_L$), and Cropland/Grazing Land$^a$

<table>
<thead>
<tr>
<th></th>
<th>ILIM</th>
<th>IPOT</th>
<th>Previous Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>62,262±3.1</td>
<td>62,970±3.0</td>
<td>61,000–72,075$^{bd,de}$</td>
</tr>
<tr>
<td>G natural ecosystems</td>
<td>44,723±3.2</td>
<td>44,723±3.2</td>
<td>49,000–56,500$^{bd,de}$</td>
</tr>
<tr>
<td>$E_L$ lakes and</td>
<td>1475±1.0</td>
<td>1489±0.9</td>
<td>760$^c$</td>
</tr>
<tr>
<td>grazing land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G cropland</td>
<td>7784±2.9</td>
<td>8501±2.3</td>
<td>6700–7980$^{bd,de}$</td>
</tr>
<tr>
<td>G irrigated crops</td>
<td>8191±2.7</td>
<td>8258±2.6</td>
<td>5800–20,400$^{bd,de}$</td>
</tr>
<tr>
<td>B irrigated crops</td>
<td>7273±2.8</td>
<td>7242±2.8</td>
<td>5704$^d$</td>
</tr>
<tr>
<td>G grazed land</td>
<td>6949±2.8</td>
<td>6936±2.8</td>
<td>5000$^g$</td>
</tr>
<tr>
<td>G irrigated grazing land</td>
<td>325±3.0</td>
<td>307±2.8</td>
<td></td>
</tr>
<tr>
<td>B irrigated grazing land</td>
<td>600±7.4</td>
<td>1258±0.8</td>
<td>1426$^l$</td>
</tr>
<tr>
<td>G grazed total</td>
<td>8155±2.7</td>
<td>8152±2.7</td>
<td></td>
</tr>
<tr>
<td>G irrigated grazing land</td>
<td>8122±2.7</td>
<td>8122±2.7</td>
<td></td>
</tr>
<tr>
<td>B grazed total</td>
<td>33±4.4</td>
<td>30±4.4</td>
<td></td>
</tr>
<tr>
<td>G irrigated grazing</td>
<td>36±10.7</td>
<td>106±1.3</td>
<td></td>
</tr>
<tr>
<td>land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G cropland</td>
<td>15,071±2.7</td>
<td>15,058±2.7</td>
<td></td>
</tr>
<tr>
<td>G irrigated</td>
<td>357±3.1</td>
<td>336±2.9</td>
<td></td>
</tr>
<tr>
<td>B total</td>
<td>636±7.5</td>
<td>1364±0.9</td>
<td>1210–1740$^{pm,ln}$</td>
</tr>
</tbody>
</table>

$^{a}$LPJML results are averages for the period 1971–2000 for both the ILIM and the IPOT simulations. The results represent the simulations under the reference precipitation data set whereas the range (%) of the other precipitation simulations is given in parenthesis. The independent estimates are for various time periods as indicated and based on varying assumptions about the distributions of cropland and of irrigated area.


$^{c}$Baumgartner and Reichel [1975].

$^{d}$L'vovich et al. [1998], evapotranspiration from land in 1980.

$^{e}$Rockström et al. [1999], various time periods.


$^{g}$Falkenmark and Rockström [2004], 1999.

$^{h}$Rockström et al. [1999], 1992–1996.


$^{j}$Postel [1998], overall consumption on croplands for 1995.

$^{k}$Postel [1998], consumption by converted pasture and natural grazing land used by livestock in 1995.

$^{l}$Molden [2007].


3. Results

3.1. Contemporary Green and Blue Water Consumption

[18] During the period 1971–2000, total agricultural water consumption was by far dominated by green water consumption on both cropland ($G = ca. 7,250$ km$^3$ year$^{-1}$) and grazing land (ca. 8,150 km$^3$ year$^{-1}$) (Table 1). Thus only in some regions and countries (e.g., in Egypt, Saudi Arabia, Pakistan) did crop production depend primarily on blue water, while in most other countries it depended basically on green water (Figures 3f and 3g). Although the total amounts of $G$ were almost the same in ILIM and IPOT, the relative contribution of $G$ was higher in ILIM ($92\%$ on cropland) than in IPOT ($85\%$), because less blue water was withdrawn in the former (green water resources, i.e., $P$, were the same in both simulations) (Table 1). Even on irrigated cropland, $35\%$ (ILIM) and $20\%$ (IPOT), respectively, of total water consumption were green by origin. Natural terrestrial ecosystems, which are sustained solely by green water, consumed an additional $44,723$ km$^3$ year$^{-1}$.

[19] Figure 3a shows the spatial distribution of $G$ from cropland per 0.5° grid cell. The highest values (>200 mm year$^{-1}$) occurred in regions with dense agricultural areas such as the central U.S., eastern Europe, India, and some Southeast Asian regions. Since these values are influenced by the fractional agricultural area of a grid cell, Figure 3b shows $G$ from cropland per unit cropland area. In this representation, the climatic conditions are reflected. Accordingly, high values of >800 mm year$^{-1}$ were prevalent in the humid tropics, e.g., in parts of the Amazon basin and Indonesia, while $G$ was relatively low in cooler and drier regions.

[20] Blue water withdrawal ($W_d$) for irrigation was $2,555$ km$^3$ year$^{-1}$ (IPOT) and $1,161$ km$^3$ year$^{-1}$ (ILIM), while blue water consumption ($B$) reached $1,364$ km$^3$ year$^{-1}$ and $636$ km$^3$ year$^{-1}$, respectively (compare Tables 1 and 2 and Figure 4). India, China, Pakistan and the U.S. are the countries with the largest amount used and consumed, together accounting for about half of the global amounts in both simulations (Table 2). We note that in ILIM only 46% of the amount in IPOT was withdrawn and consumed globally, meaning that more than half of the water involved in irrigation was taken from nonrenewable or nonlocal water resources. In individual countries, the difference between IPOT and ILIM turned out to be even larger (Table 2). Generally, our IPOT estimates of $G$, $B$, and $W_d$ lie well within the range documented by earlier studies, while the estimates of $B$ and $W_d$ in ILIM are usually lower (Tables 1 and 2 and Figure 4). Note that the documented range is rather large, and that the underlying data are for different time periods and therefore not directly comparable (see below for discussion).
Irrespective of the simulation, \( B \) was concentrated in intensively irrigated areas such as the lower Nile and the Indus basins as well as parts of the western U.S. (Figure 3c). Averaged over entire grid cells, highest values were found for parts of India (>200 mm year\(^{-1}\) in IPOT). If averaged over the irrigated area only, highest values (\( B > \) 800 mm year\(^{-1}\) under IPOT; Figure 3d) occurred, e.g., in Mexico, in southern India, the Mediterranean region and parts of Southeast Asia, reflecting the warm and (seasonally) dry climatic conditions in these regions that lead to high values of NIR and, thus, \( B \).

### 3.2. Temporal Variability in Green and Blue Water Consumption

While the above sections report on average green and blue water flows for the recent three decades, we here investigate the temporal changes in \( G \) and \( B \) as related to climatic variability and the spatial extent of cropland for the entire simulation period 1901–2003. This analysis was performed for the growing periods only, because correlation of time series of year-round climate and water consumption would not be meaningful. We found that although there was pronounced interannual variability in \( G \) and \( B \), more green...
IPOT and ILIM apparently became larger in the course (see Figure 5a) of the century (see circles in Figure 5b), partly because especially the driest rainfed areas may have been converted to irrigated areas. Similarly, B in the IPOT simulation showed a slightly decreasing trend over the century, apparently because the irrigated area assumed to exist in 1901 (rice fields, see Appendix A1) received on average somewhat more P than the areas that were irrigated more recently (see circles in Figure 5c). In general, B per unit irrigated area was two to three times higher than G per unit rainfed area over the entire period (Figures 5b and 5c), which reflects the higher water use intensity on irrigated land.

3.3. Global Effects of Land Cover Change and Irrigation

To assess the impacts of both anthropogenic land cover conversion and irrigation upon the global water balance, we compared the results between PNV and INO (to derive the isolated land cover change effect), and between INO and, respectively, IPOT and ILIM (to derive the isolated irrigation effect). We found that land cover change alone (PNV minus INO) decreased evapotranspiration by 1.763 km$^3$ year$^{-1}$ (2.8%) and increased river discharge ($Q$) by the same amount (equaling 5.0%, see Table 3). The increase in $Q$ followed mainly the patterns of agricultural expansion and was highest in the central U.S., eastern Europe, and some eastern Asian regions (compare Figure 6a). Productive water consumption ($E_T$) under PNV was almost 8% higher than under INO. Thus deforestation has reduced global $E_T$, for example due to shorter growing periods (i.e., intermittent periods with fallow land) or lower rooting depths of crops as compared to the potential forests. These changes were apportioned differently to the diverse ecosystem types, with the deforestation of tropical forests having contributed most [Rost et al., 2008]. Note, however, that the lower $E_T$ was partly counterbalanced by increased soil evaporation $E_S$ in particular (Table 3).

Irrigation led to a global increase in evapotranspiration by 0.7% in ILIM (457 km$^3$ year$^{-1}$, see ILIM minus INO in Table 3) and by 1.9% (1,165 km$^3$ year$^{-1}$) in IPOT. These increases were somewhat lower than the values of B (see Table 2), as irrigation increases the amount of green soil water to enter subsurface runoff because of the higher overall soil water content. The influence of irrigation on global $Q$ was a decrease of 1.2% in ILIM and of 0.5% in IPOT (Table 3). The lower decrease of $Q$ in IPOT was due to the assumed extraction of e.g., nonrenewable or remote blue water (amounting to 967 km$^3$ year$^{-1}$ globally), which partially entered the return flow and thus increased $Q$. Large reductions in $Q$ were simulated under IPOT for rivers like the Euphrates, Syr Darya, Amur Darya, Colorado, and Huang He (Figure 6b).

Figure 4. Comparison of LPJmL-computed blue water withdrawal (a) and consumption (b) under potential (IPOT) and limited (ILIM) irrigation (km$^3$ year$^{-1}$, 1971–2000 averages) with other studies (Shiklomanov and Rodda [2003], 1970–2000; WRI [1998], different years between 1987 and 1995; FAO [2003], 1998–2002; Döll and Siebert [2002], 1971–2000; Döll and Siebert [2002], 1998–2002; the latter two represent IPOT-like model estimations). The error bars of IPOT and ILIM indicate the precipitation uncertainty, and the error bars of the independent estimates in Figure 4a indicate the range of values across the considered studies.
Table 2. Country-Scale Estimates (km$^3$ yr$^{-1}$) of Agricultural Blue Water Withdrawal ($W_d$) and Consumption ($B$)$^a$

<table>
<thead>
<tr>
<th>Country</th>
<th>$W_d$ (km$^3$ yr$^{-1}$)</th>
<th>Previous Estimates</th>
<th>$B$ (km$^3$ yr$^{-1}$)</th>
<th>Previous Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LPJmL IPOT ILIM</td>
<td></td>
<td>LPJmL IPOT ILIM</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>404–409</td>
<td>253–267</td>
<td>352–408$^{b,c,d}$</td>
<td>203–206</td>
</tr>
<tr>
<td>India</td>
<td>710–715</td>
<td>181–203</td>
<td>353–655$^{b,c,d}$</td>
<td>385–387</td>
</tr>
<tr>
<td>Indonesia</td>
<td>40–42</td>
<td>13–14</td>
<td>13–69$^{b,c}$</td>
<td>18–19</td>
</tr>
<tr>
<td>Pakistan</td>
<td>117–120</td>
<td>35–57</td>
<td>97$^b$</td>
<td>54–55</td>
</tr>
<tr>
<td>Vietnam</td>
<td>46–50</td>
<td>24–29</td>
<td>23–47$^{b,c}$</td>
<td>19–23</td>
</tr>
<tr>
<td>Egypt</td>
<td>29–30</td>
<td>14</td>
<td>47–60$^{b,d}$</td>
<td>17</td>
</tr>
<tr>
<td>South Africa</td>
<td>13</td>
<td>5</td>
<td>10–11$^{b,d}$</td>
<td>7</td>
</tr>
<tr>
<td>Spain</td>
<td>19</td>
<td>8–11</td>
<td>19–35$^{b,d}$</td>
<td>12–13</td>
</tr>
<tr>
<td>United States</td>
<td>167–171</td>
<td>92–97</td>
<td>186–196$^{b,d}$</td>
<td>104–105</td>
</tr>
<tr>
<td>World</td>
<td>2,534–2,566</td>
<td>1,161–1,249</td>
<td>2,236–2,942$^{b,c,e,g}$</td>
<td>1,353–1,375</td>
</tr>
</tbody>
</table>

$^a$LPJmL results are averages for the period 1971–2000 for both the IPOT and ILIM simulation. The ranges indicate the minimum and maximum results for the different precipitation inputs. The independent withdrawal estimates are for various time periods as indicated.

4. Discussion

4.1. General Findings

[29] On the basis of a coupled hydrologic and biogeochemical process model, this study provides the first spatially and temporally explicit assessment of water consumption in both rainfed and irrigated agriculture, while distinguishing between the individual contributions of blue water withdrawn for irrigation and green water stemming directly from precipitation. The findings of the study underscore in several aspects the observation that humans are influencing the terrestrial water cycle to a degree that is visible at global scale [Vörösmarty and Sahagian, 2000]. Firstly, we demonstrate quantitatively that global water withdrawal and consumption in agriculture by far exceeds the amount suggested in previous studies that were based on blue (irrigation) water only, as green water consumption from rainfed agricultural land (including the rainfed part of irrigated land) was significantly higher than the blue water consumption. Secondly, we find that global irrigation nonetheless has left a noticeable signature (though globally marginal) in the terrestrial water balance in intensively irrigated areas. Thirdly, up to about half of the global blue water withdrawal for irrigation was found to draw from nonrenewable and/or nonlocal water resources. Fourthly, the effect of global land cover change was shown to be significantly larger than the irrigation effect, while both effects increased in magnitude over the past century. Also,
fifthly, our findings are robust against uncertainties in precipitation inputs.

4.2. Green and Blue Water Consumption

[30] The fact that green water plays a major role for sustaining global food production in most countries of the world (see Figure 3g) has been noted earlier [Falkenmark and Rockström, 2004; Molden, 2007]. For a number of countries, however, we found a somewhat stronger green water dependency than documented in those studies. We presume the present results to be more realistic, since we assessed $G$ at higher spatial resolution, distinguished its contribution on irrigated land, considered the intra- and interannual dynamics of both $G$ and $B$, and quantified them jointly in an internally consistent, process-based accounting framework. Note that we quantified $G$ for a whole year, i.e., including the periods outside of the growing periods of the crops. If, alternatively, only the water consumed during the growing periods was accounted for (data not shown), we would arrive at approx. 55% lower estimates of $G$ from cropland (rainfed plus irrigated), and the global share of blue water on global agricultural water consumption would be slightly increased from 15% to 23% (ILIM), and from 8% to 13% (IPOT), respectively. Falkenmark and Rockström and other studies that quantified $B$ and $G$ did not specify whether, and to what extent, the water consumption outside of the growing periods was considered, but the general proximity of our values to previous estimates suggests that those conventionally also referred to entire years (see Table 2).

[31] $Wd$ and $B$ as computed in IPOT were more than twice as large as in ILIM, and they were closer to previously reported amounts (Figure 4, Table 2). Furthermore, NIR in IPOT agrees well with the estimates in Döll and Siebert [2002] (data not shown). The good agreement between our IPOT values to the documentary evidence suggests that a major part of the water involved in global irrigation - up to 55% or ~1,400 km$^3$ year$^{-1}$ (withdrawal) and ~730 km$^3$ year$^{-1}$ (consumption), respectively, in 1971-2000 - stemmed from nonrenewable and locally not accessible supplies, while this amount notably increased during the past century. Note, however, that IPOT neglects the possibility of reduced (supplementary) irrigation when overall water resources are scarce, that is, IPOT overestimates real $Wd$ and $B$ in these cases.

4.3. Consumption of Nonrenewable and Nonlocal Blue Water

[32] To our knowledge, the only figure that is comparable to our ILIM estimates are those provided by Vörösmarty et al. [2005], who suggest that 16–33% of agricultural water withdrawal (400–800 km$^3$ year$^{-1}$) is nonsustainable, i.e., exceeding locally accessible supplies or drawing from fossil groundwater. This is less than found here, partly because...
Vörösmarty et al. used a larger surrounding area of 75 km from which water for irrigation can be secured whereas we assumed only one neighbor cell from which additional water could be taken. The spatial pattern of the over use of blue water found here (Figure 3e), however, largely agrees with that found by [Vörösmarty et al., 2005, Figure 7.3] and also with observations. It is known, for example, that groundwater is used to a large degree in the most important irrigating countries such as India (annual withdrawal, 190 km³), China (53 km³) and the U.S. (110 km³) [FAO, 2003]. In addition, the capacity of desalination plants in Kuwait, the United Arab Emirates, the U.S. and Saudi Arabia yielded between 0.5 and 1.8 km³/yr per country in 1996 [Gleick, 1998]. If all these amounts were added to our ILIM simulation results, the country totals would be in line with documentary evidence (compare Table 2), suggesting that the differences between the IPOT and the ILIM results represent plausible estimates of the withdrawal and consumption of nonrenewable/non-local water. Note, though, that the renewable part of groundwater is inherent both to our results (base flow component of $R$) and to above statistics (the individual contributions of renewable and nonrenewable ground water resources to groundwater use are not known for most countries, though Vörösmarty et al. suggest a value of ca. 200 km³ year⁻¹).

4.4. Effects of Land Cover Change and Irrigation

There is strong evidence that changes in land cover [e.g., Eshleman, 2004; Siriwardena et al., 2006], irrigation [e.g., Boucher et al., 2004; Haddeland et al., 2006], and the combination of both [Scanlon et al., 2007; Haddeland et al., 2007], affect water balances at scales from local to global. Deforestation typically reduces evapotranspiration (e.g., through lower rooting depths and extended periods with fallow land) and thereby increases Q, while irrigation should decrease Q through the water withdrawals and thus increase evapotranspiration. The present results - which show a 5% increase in global Q through changes in land cover (mainly deforestation) and a decrease by at least 0.5% through irrigation (IPOT) (Table 3) - principally corroborate these observations.

However, our finding that the net effect of land cover conversion and irrigation has increased Q (4.4%) and decreased land evapotranspiration (0.9%) differs from the finding of Gordon et al. [2005], who found that these effects cancel each other out at the global scale. This difference can be explained by the fact that Gordon et al. obviously overestimated the irrigation effect, since it appears to have been based on irrigation water withdrawal rather than consumption, and because the individual processes involved in irrigation (e.g., irrigation requirements and efficiencies) were not explicitly considered. For example, the fact that...
constant over time. This could be improved by accounting for the years of reservoir induction [Shiklomanov and Rodda, 2003] as well as for historic country- or regional-scale information on the extent of irrigated areas, pending progress in the construction of such databases. It is unlikely, however, that these improvements will change our general conclusion that the global effects of land cover change and irrigation have increased continuously. In an ongoing study (Dieter Gerten, unpublished data) it is being investigated whether, and where, the anthropogenic impacts upon global Q found here have been stronger than the effects of climatic variations and of the rising atmospheric CO$_2$ content, as suggested by Gedney et al. [2006]. In addition, Rost et al. [2008] showed that the effects of land use change and irrigation in the future may well be as strong as climate change effects.

4.5. Potential Uncertainties

[36] It is possible that e.g., B in the ILIM simulation is underestimated due to uncertainties in the input data used here. Investigations for available discharge gages in northern India - where the difference between IPOT and ILIM was most pronounced (Table 2, Figure 3e) - revealed that observed $P$ aggregated over the upstream area was lower than observed $Q$ (compare Figure 7c). This suggests an underestimation of regional $P$, which inevitably resulted in low values of $Q$ and, consequently, $B$. We note that observed $Q$ probably includes the return flow of irrigation water withdrawn from deep groundwater or other, nonlocal sources (not considered in ILIM), but the IPOT simulation showed that this additional amount of water would not be sufficient to explain the divergence between observed $P$ and $Q$. In some (semi) arid regions, $Q$ (and, thus $B$ in ILIM) may be overestimated because of the underestimation of evaporation losses [Gerten et al., 2004b]. Nonetheless, at continental- or global-scale effects of $P$ uncertainties upon our results are small (maximum range of 7.5% in $Wd$ and $B$ in ILIM; range between ILIM and IPOT of 5.5% in $Wd$ and of 5.1% in $B$; Table 2, Figure 4). As a result, $B$ and $G$ were rather insensitive to the different $P$ data sets used here (Table 1), as were the relative changes due to land cover change and irrigation in water consumption as well as $Q$ (Table 3). Uncertainties in $P$ input have been systematically analyzed in a comprehensive hydrologic validation of LPJmL (Biemans et al., submitted manuscript, 2008).

[37] It can also not be precluded that the size of the irrigated area used in the present study is somewhat overestimated especially for northern India, since other, satellite-based data products suggest a smaller extent there [Siebert et al., 2005]. Moreover, we may slightly under- or overestimate the water withdrawal from surface water bodies in ILIM, as reservoir management, which influences the storage and availability of water in the river system, is not yet considered. This can be improved in the future by implementing global reservoir management in the model (following e.g., Hanasaki et al. [2006]). The modeled crop phenology and biomass has been extensively validated in a previous study [Bondeau et al., 2007], but we note that the irrigation priority list adopted here was derived mostly from European agricultural practices. This may affect the amounts of $B$ for individual crops, but probably less so the CFT-averaged results presented here. Furthermore, this study assumes a fixed depth of soil, and our soil classifica-

Figure 7. LPJmL-simulated annual river discharge (m$^3$ s$^{-1}$) for the PNV (orange) and ILIM (blue) simulation compared to observations (black) from the global river discharge database (http://www.sage.wisc.edu/riverdata/) for (a) the Mississippi River (USA, Helena Ark., area: 2928254 km$^2$), (b) the Danube (Romania, Ceatal Izmail, 80700 km$^2$), and (c) the Ravi (India, Mukesar, 5703 km$^2$). The gray bands indicate the range in discharge of the ILIM simulation according to different precipitation inputs. The gray line in Figure 7c shows $P$ from the reference dataset.

nonrenewable blue water is exploited and brought to the field in IPOT may in some regions lead to an increase in $Q$ (compared to INO) to the extent that this additional water enters return flow. This also explains why $Q$ is decreased less in IPOT than in ILIM.

[35] Both the land cover and the irrigation effect on evapotranspiration and $Q$ intensified in the course of the 20th century, basically following the increasing trend in the global areas under cultivation and irrigation, respectively. For the period 1901–1930, we found a land cover change effect of 3.2% and an irrigation effect of $-0.7\%$ on global $Q$ (ILIM; data not shown), which is lower than for the recent decades (see Table 3; also compare Figure 5a). Note that this trend and the computed interannual and interdecadal dynamics of $G$ and $B$ are affected by the lack of global data on irrigated areas and reservoirs in operation, for which reason we assumed their present distribution having been used here.

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed</th>
<th>PNV</th>
<th>ILIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>12345</td>
<td>12345</td>
<td>12345</td>
</tr>
<tr>
<td>1970</td>
<td>12345</td>
<td>12345</td>
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</tr>
</tbody>
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C. Overview of the LPJmL Model

The LPJmL model simulates key ecosystem processes such as photosynthesis, evapotranspiration, autotrophic and heterotrophic respiration, as well as allocation of assimilated carbon to different above- and below-ground pools. It considers nine natural plant functional types (PFTs) and twelve crop functional types (CFTs), which correspond to the world’s most important field crops (temperate cereals, temperate roots, tropical cereals, tropical roots, rice, maize, pulses, sunflower, soybean, groundnuts, rapeseed) and pasture (grazing land). Carbon fluxes and vegetation dynamics are directly coupled to water fluxes in the model, in that, e.g., photosynthesis and transpiration are treated as simultaneous processes [Sitch et al., 2003; Gerten et al., 2004b]. The PFTs can coexist in any grid cell, but their abundance depends on competition for light, water (e.g., through distribution of fine roots) and space as well as on environmental (e.g., bioclimatic) constraints. This way, the distribution, fractional coverage and seasonal phenology of PFTs change depending on climate, water availability, and disturbances such as fire. A grid cell can contain several stands differentiated between rainfed and irrigated CFTs and one stand for PFTs. Each stand in a grid cell shares the same climate input, but the water balance is computed separately. The growing season of CFTs is initiated by sowing and ends with harvest when maturity is reached. The date of sowing is modeled as a function of temperature in the case of temperate-zone CFTs and as a function of precipitation (depending on a soil moisture threshold) in the case of tropical CFTs. Multiple annual cropping of rice is allowed for warm regions with short growing periods [Bondeau et al., 2007].

A priority list has been established, estimating which crops are most likely to be irrigated, and in what sequence this occurs. Areas equipped for irrigation [Siebert et al., 2007] (Figure 2a) were assumed to increase from the year 1901 (when no irrigation was considered except for rice) to their 2000 value in each grid cell, following the global trend of irrigation area provided by Evans [1997]. Irrigation area in the years 2001–2003 was assumed to follow the trend of the last 20 years of that period.

A2. General Soil Water Balance

This section provides a brief description of the daily water balance and its coupling to vegetation as modeled in LPJmL (more details in Gerten et al. [2004b, 2007]; for illustration, see Figure 1). The soil is divided into two layers; 0.5 and 1 m thick. Water holding capacity and hydraulic conductivity vary among grid cells according to soil texture derived from the FAO global database [FAO, 1991] (see details in Sitch et al. [2003]). The absolute water content $W$ of the soil layers per stand at day $t$ depends on the previous day’s value $W_{t-1}$, and the balance between the amount of water infiltrating into the soil (precipitation $P$, snowmelt $M$ and irrigation water $Irr$ minus interception loss from leaves $E_I$) and that removed from the soil through runoff $R$, soil evaporation $E_S$, plant transpiration $E_T$, and percolation $p$ (all in mm d$^{-1}$):

$$W_t = W_{t-1} + (P + M + Irr - E_I) - R - (E_S + E_T) - p \quad (A1)$$

$R$ is defined as the sum of the excess of water over field capacity of the two layers and a base flow component [Gerten et al., 2004b].

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A3. Productive Water Consumption (Plant Transpiration)

[43] We define productive water consumption $E_T$ (mm d$^{-1}$) as the amount of water, either from precipitation (green) or from irrigation (blue), which is transpired by a CFT or PFT. $E_T$ is determined for each CFT and PFT as the lesser of an atmosphere-controlled demand $D$ and a supply $S_Y$:

$$E_T = \min(S_Y, D) \quad (A2)$$

$S_Y$ is regulated by soil moisture and plant hydraulic traits; when the soil is saturated, it reaches a maximum $E_{max}$ (5 mm d$^{-1}$) and declines linearly with relative soil moisture $W_r$, i.e., the quotient of $W_r$ and plant-available field capacity, weighted by the CFT- and PFT-specific fraction of roots present in a layer ($f_d$):

$$S_Y = E_{max} \cdot W_r \cdot f_d \quad (A3)$$

$D$ is a function of potential evapotranspiration $E_{pot}$ (mm d$^{-1}$) and potential, not water-limited canopy conductance of carbon and water $g_{pot}$ (mm s$^{-1}$):

$$D = \frac{(1 - f_{wet}) \cdot E_{pot} \cdot \alpha_m}{1 + g_m/g_{pot}} \quad (A4)$$

where $f_{wet}$ is the fraction of the day that the canopy is wet; $E_{pot}$ is determined according to the Priestley-Taylor method based on latitude, net radiation, and temperature (details in Stöch et al. [2003]); $\alpha_m$ is a maximum Priestley-Taylor conductance (1.391) and $g_m$ is a scaling coefficient (3.26 mm s$^{-1}$). If $D > S_Y$, $E_T$ is reduced and plants experience water limitation (for details, see Gerten et al. [2007]).

A4. Unproductive Water Consumption (Interception Loss and Evaporation)

[43] Unproductive water consumption consists of interception loss $E_I$, and evaporation from soil $E_S$, lakes $E_L$ and canals $E_C$ (all in mm d$^{-1}$). In our model, $E_S$ depends on $E_{pot}$, the Priestley-Taylor coefficient $\alpha = 1.32$, the relative moisture in the upper 0.2 m of the soil column ($W_{20}$), and the bare soil fraction of a stand, which is computed from the fractional coverage with vegetation $f_c$ and the daily status of PFT- and CFT-specific leaf phenology (phen):

$$E_S = E_{pot} \cdot \alpha \cdot W_{20}^2 \cdot (1 - f_c \cdot \text{phen}) \quad (A5)$$

$E_I$ is determined as follows, where $LAI$ is the leaf area index, and $i$ a dimensionless biome-dependent proxy for the rainfall regime [Gerten et al., 2004b]:

$$E_I = \min(LAI \cdot i \cdot \text{phen}, P + Irr, E_{pot}) \cdot f_i \quad (A6)$$

$E_L$ is assumed to equal $E_{pot}$; $E_C$ is considered a constant fraction of conveyance loss in irrigation systems (see below).

A5. Blue Water Withdrawal and Consumption

[46] Blue water consumption is defined herein as the amount of productively or unproductively evapotranspiring irrigation water that originates e.g., from river segments, aquifers, lakes and reservoirs, as opposed to the “green” part of soil water that originates directly from precipitation. To compute the blue water stocks and flows, the existing LPJmL model was enhanced by several features, and a methodology was developed to separate green and blue water flows on irrigated areas, as described in the following and illustrated in Figure 1.

A5.1. River Routing Module

[47] A river routing module was implemented in LPJmL to compute the daily transitional discharge volume in each 0.5° grid cell (see Figure 2a). To determine the transport directions we used the global 0.5° drainage direction map DDM30 of Döll and Lehner [2002]. DDM30 organizes the Earth’s land area into drainage basins and provides the river network topology, assuming that each grid cell can drain into one of the eight neighboring cells. Each grid cell is considered to have a surface water storage pool, and the change with time $t$ of water storage $S$ (mm d$^{-1}$) is represented as:

$$\frac{dS}{dt} = \frac{dS_{riv}}{dt} + \frac{dS_L}{dt} - C_{DL} - Wd \quad (A7)$$

$S_{riv}$ is the water storage in rivers, $S_L$ is the water storage in lakes/reservoirs, $C_{DL}$ is the domestic, industrial and livestock water consumption, and $Wd$ is water withdrawn for irrigation (all in mm d$^{-1}$, and described below). In reality, additional stores exist (such as fossil groundwater, water from desalination plants and from diverted rivers), but these are not explicitly computed in this study because of the lack of global data on (deep) groundwater stocks and flow directions and because man-made river diversions are not accounted for in the river topology used. To estimate the amount of these resources, we performed two model runs, in which we either use $S$ as given by equation (A7) (ILIM simulation) or assume unlimited blue water resources in irrigated areas (IPOT simulation) (see below for specification).

[48] The change over time of $S_{riv}$ is represented as a continuity equation (as also used by Bosilovich et al. [1999]) derived from a linear reservoir model [Huggins and Burney, 1982]:

$$\frac{dS_{riv}}{dt} = (Q_{in} - Q_{out} + Q_{out}) \cdot \frac{1}{f} + R \quad (A8)$$

$Q_{in}$ is the input of discharge from upstream grid cells, $Q_{out}$ is the output to the downstream cell, $Q_{out}$ (see below) is the outflow of lakes and reservoirs in the respective cell (all in m$^3$ d$^{-1}$), $f$ is a factor (0.001) to convert the volumetric amounts to mm d$^{-1}$ by weighting with the area $A$ (m$^2$) of the cell, and $R$ is the runoff generated in the cell.

[49] A generally applied assumption for the water transport equation is that $Q_{out}$ is a linear function of $S_{riv}$:

$$Q_{out} = S_{riv} \cdot \frac{v}{d} \quad (A9)$$

where $v$ is the flow velocity (m d$^{-1}$) and $d$ the distance (m) between the midpoints of the considered cells. At 0.5° resolution, the latter ranges between 6 km in subarctic regions and 79 km at the equator. We assume a globally constant flow velocity of 1 m s$^{-1}$ also used in Döll et al.
This flow velocity is equivalent to 86.4 km d⁻¹, so that the whole water storage of the considered cell flows out and passes more than one grid cell per day. Equation (A9) considers only the flow to the next downstream cell. The maximum of v/d has to be 1 to deliver reasonable results, e.g., d has to be greater than v, which is never the case in our 0.5° model application. While other studies worked at higher resolutions or used shorter time steps, we accumulated the distances over downstream cells until d becomes greater than 86.4 km

\[
d = \sum_{j=1}^{n} d_{i-1,j}
\]

where \(d_{i-1,j}\) is the distance between connected downstream cells \(i\). The outflow \(Q_{\text{out}m}\), from the considered cell to the downstream cell \(n\) is then determined with equation (A9). The remaining difference between \(S_{\text{Riv}}\) and \(Q_{\text{out}0,n}\) is the outflow from the original cell to the downstream cell \(n = 1\).

### A5.2. Lakes and Reservoirs

[50] Besides rivers, we took lakes and reservoirs into account as additional stores of water (\(S_L\), mm). For each grid cell we derived the area occupied by open freshwater bodies from the global data set generated by Lehner and Döll [2004]. Their daily vertical water balance was assumed to be the difference between \(P\) and \(E_{\text{wet}}\). As a lateral component, upstream discharge \(Q_{\text{up}}\) (see equation (A8)) is used as inflow to the lakes and reservoirs. The outflow \(Q_{\text{outf}}\) (m³ d⁻¹) was calculated using a simple approach following Döll et al. [2003]. It depends on the actual active storage \(S_L\) and the maximum active storage capacity \(S_{L,\text{max}}\) (both in m³), the latter being computed as the product of the area of the lake (m²) and the maximum active storage depth, set to 5 m:

\[
Q_{\text{outf}} = 0.01 \cdot S_L \cdot \left( \frac{S_L}{S_{L,\text{max}}} \right)^{1.5}.
\]

### A5.3. Domestic, Industrial and Livestock Water Consumption

[51] Annual values of domestic, industrial and livestock water consumption \(C_{\text{DIL}}\) (mm) were provided for each grid cell by the Global Water Use model of WaterGAP 2 (Stefan Siebert, personal communication). The domestic sector includes household use, small businesses and other municipal uses, the industry sector includes power plants and manufacturing facilities. The water intensity (per unit use of water) has been determined for each sector and multiplied by the main driving forces of sectoral water use (population, national electricity production and number of livestock, respectively) [Alcamo et al., 2003a]. Globally, these consumptions amounted to 94 km³ year⁻¹ averaged over 1971–2000. We assumed an equal distribution of \(C_{\text{DIL}}\) over the year, and the daily amount was withdrawn from \(S\), a cell’s concurrent water storage (see equation (A7)). For days when \(S\) was insufficient to meet this requirement, e.g., during low-flow periods, the respective amount is summed up and withdrawn later as it became available. \(C_{\text{DIL}}\) can be regarded as a part of human blue water consumption, but since the present study focuses on agricultural water consumption, it is not discussed further.

### A5.4. Irrigation Efficiency and Amount

[52] We define a net irrigation requirement \(NIR\) (mm) as the amount of water required to avoid crop water limitation and not provided by rainfall (see below). However, as irrigation is mostly rather inefficient [Box and Niegelen, 1990], actually more water is withdrawn than needed by the plants. This water is lost in applying it to the crops, e.g., by evaporation from open channels, from soils and vegetation canopies, by leakage from pipelines, and by seepage (these redistributions are implicitly computed by our model, see equations (A5), (A6), (A14)). The total amount of withdrawn water is the gross irrigation requirement \(GIR\) (mm). The ratio between \(NIR\) and \(GIR\) is given by the irrigation project efficiency \(e_P\) (see also Figure 1).

[53] To account for \(e_P\) and its spatial distribution, we used the country-scale data set compiled by Rohwer et al. [2007] (see Figure 2b), who derived \(e_P\) from the product of an application system efficiency, a conveyance system efficiency and a management factor. The application efficiency describes losses when water is applied to the field. It differs between surface, sprinkler, and micro-irrigation; values vary between 0.6 in countries with mainly surface irrigation and 0.9 in countries with mainly micro-irrigation (such as Israel, Jordan and the United Arab Emirates). The conveyance efficiency \(e_C\) describes losses during the transport of water from a source to the field; values range from 0.7 in countries with predominantly open canals of surface irrigation systems (in large parts of Asia, Africa, Latin America, and Australia) to 0.95 in countries with well-maintained pressurized pipeline systems (in Russia and western/northern Europe [Rohwer et al., 2007]). The management factor is a substitute of across-field distribution efficiency that describes the type of management and maintenance of irrigation schemes. The complexity of management typically increases with the size of irrigation projects, thus values range from 0.7 for countries with expanded large-scale surface irrigation systems (e.g., Pakistan, Thailand, Chile, Mexico, and Sudan) to 1 for small-scale systems. The resulting project efficiency is highest (>0.8) in countries with micro-irrigation and lowest (around 0.3) in countries with large-scale surface irrigation systems [Rohwer et al., 2007] (see Figure 2b). The aggregated values of \(e_P\) used here agree well with the regional averages provided by Döll and Siebert [2002], but since the present values have been determined for the countries of the world, they exhibit more spatial detail.

[54] The irrigation amount on areas equipped for irrigation was determined in three steps. First, \(NIR\) was calculated, assuming that irrigation only occurs if a crop is water-limited, i.e., if \(D > Sy\) (cf. equations (A3) and (A4)). In that case, \(NIR\) was computed as the product of the upper soil layer’s water holding capacity (WHC), and the minimum of the water amount required to satisfy the condition \(Sy = D\) and that needed to reach field capacity of the upper layer (accounting for the fact that \(Sy\) must not exceed \(E_{\text{max}}\) see equation (A3)):

\[
NIR = \min \left( \frac{WR}{f_k} \cdot \left( \frac{D}{Sy} - 1 \right), 1 - W \right) \cdot WHC
\]

Second, \(GIR\) was computed as the quotient of \(NIR\) and \(e_P\) of the country in which a cell is located. Third, the amount of
water withdrawn $W_d$ (mm) as dependent on GIR and current water storage $S$ (see equation (A7)) was determined.

[55] In practice, schedules rule the timing of irrigation, that is, crops are not always being irrigated if there is water limitation [Brower et al., 1989]. We assumed an irrigation interval depending on soil moisture, reflecting farmers’ decisions made on the basis of weather conditions: If $W_d$ fell below 0.9 (90% of field capacity) and $D < S$, GIR was determined, withdrawn from $S$ (if available), and applied to the field in the same way as precipitation.

A5.5. Simulations of Limited and Potential Irrigation

[56] We adopted two alternative approaches for estimating the amount of blue irrigation water that can be withdrawn and brought to the field. In the IPOT simulation, the whole amount of irrigation water $Irr_{pot}$ (mm) was withdrawn ($W_d = GIR$) without checking whether $S$ can fulfill this demand. That is, we assumed that water availability is always guaranteed, which is a reasonable approach since e.g., fossil groundwater resources and remote water resources (not covered by $S$) are exploited to a large, but unknown, degree [e.g., Döll and Siebert, 2002, Gordon et al., 2005]. Note, however, that this approach neglects supraregional blue water limitations and farmers’ choices to avoid irrigation even if crops are water limited. Only the water loss during conveyance $L_C$ was subtracted:

$$Irr_{pot} = GIR - L_C$$

(A13)

where $L_C$ depends on conveyance efficiency $e_C$ (see above):

$$L_C = W_d \cdot (1 - e_C)$$

(A14)

We assumed 50% of $L_C$ to evaporate ($E_C$) and the other half to return as runoff (Figure 1).

[57] In the ILIM simulation, we emulated a situation in which nonsustainable blue water resources such as fossil groundwater, desalinated sea water, or water diverted from distant river basins are ignored, in that we constrained $W_d$ by $S$ (cf. equation (A7)). If $S$ was insufficient to fulfill GIR, we only assumed additional water $W_{d,a}$ (mm) to be withdrawn from the neighboring cell with the largest upstream area to represent conveyance systems and transportation of water by trucks over limited distances (i.e., large-scale interbasin transfers or river diversions like in California [e.g., Schoups et al., 2005] are not taken into account). The amount of blue water $Irr_{lim}$ (mm) brought to the field was thus given by:

$$Irr_{lim} = \min(GIR, W_d + W_{d,a}) - L_C$$

(A15)

[58] The difference between $Irr_{pot}$ and $Irr_{lim}$ represents the maximum consumption of blue water resources other than those available in situ in rivers, lakes, reservoirs, and renewable groundwater.

A6. Blending of Green and Blue Water on Irrigated Land

[59] On irrigated areas, part of the water used by crops is blue by origin ($Irr_{lim}$ or $Irr_{pot}$), while another part is green by origin (see Figure 1). To quantify the individual fractions of blue and green water, the ratio between irrigation water and precipitation water was taken into account. The fraction of blue irrigation water intercepted by vegetation $f_b$ (compare $E_I$ in equation (A1)) is given by:

$$f_b = \frac{Irr}{P + Irr}$$

(A16)

where $Irr$ represents either $Irr_{lim}$ or $Irr_{pot}$. The green and blue proportions of the water that infiltrates into the soil were determined according to the same ratio. $E_S$ and $E_P$, however, rely on the water stored in the soil over a number of consecutive days. This fraction of blue water in the soil $f_b$ at time $t$ changes with the relative input of $P$ and $Irr$. It was thus determined as the sum of blue water at time $t - 1$ and the input from $Irr$ at time $t$ divided by the total water content in the upper soil layer:

$$f_b = \frac{W_{t-1} \cdot f_{b,t-1} + (W_t - W_{t-1}) \cdot f_{b,t}}{W_t}$$

(A17)

The fraction of blue water in the evaporation layer $f_{b, evap}$ was determined analogously according to its water content. For the lower soil layer the fraction of irrigation water in the upper soil layer was used. Thus total blue water consumption of irrigated land $B$ (mm) is:

$$B = E_T \cdot f_b + E_S \cdot f_{b, evap} + E_I \cdot f_b + E_C$$

(A18)

Total green water consumption $G$ (mm) on either irrigated or rainfed land is given analogously:

$$G = E_T \cdot (1 - f_b) + E_S \cdot (1 - f_{b, evap}) + E_I \cdot (1 - f_b)$$

(A19)

$G$ was determined as the daily sum of $G$ of all CFTs and then aggregated over a whole year, that is, unproductive evaporation as well as transpiration and interception from grasses that establish on the fallow land outside of the CFTs’ growing periods were accounted for. $B$ was counted during the growing (irrigation) period and after harvest until $f_b = 0$.

A7. Notation of Water Fluxes and Stores

$B$ Blue water consumption on irrigated land [mm d$^{-1}$]
$C_{DIL}$ Domestic, industrial and livestock water consumption [mm d$^{-1}$]
$D$ Transpirational demand [mm d$^{-1}$]
$E_C$ Evaporation from canals [mm d$^{-1}$]
$E_I$ Canopy interception loss [mm d$^{-1}$]
$E_L$ Evaporation from lakes [mm d$^{-1}$]
$E_{pot}$ Potential evapotranspiration [mm d$^{-1}$]
$E_S$ Soil evaporation [mm d$^{-1}$]
$E_T$ Plant transpiration (productive water consumption) [mm d$^{-1}$]
$e_C$ Conveyance loss efficiency [-]
$e_P$ Irrigation project efficiency [-]
$G$ Green water consumption originating from precipitation on either irrigated or rainfed land [mm d$^{-1}$]
$GIR$ Gross irrigation requirement [mm d$^{-1}$]
$Irr_{lim}$ Irrigation water reaching the field in ILIM [mm d$^{-1}$]
Irrigation water reaching the field in IPOT 

$[\text{mm d}^{-1}]$

$L_C$ Water loss in conveyance systems $[\text{mm d}^{-1}]$

$NIR$ Net irrigation requirement $[\text{mm d}^{-1}]$

$P$ Precipitation $[\text{mm d}^{-1}]$

$Q_{in}$ Inflow of discharge from upstream grid cells $[\text{m}^3 \text{ d}^{-1}]$

$Q_{out}$ Outflow of discharge to downstream grid cells $[\text{m}^3 \text{ d}^{-1}]$

$Q_{out}$ Outflow of lakes and reservoirs $[\text{m}^3 \text{ d}^{-1}]$

$R$ Surface and subsurface runoff $[\text{mm d}^{-1}]$

$S$ Total water storage in a grid cell $[\text{mm}]$

$S_s$ Water storage in lakes and reservoirs $[\text{mm}]$

$S_{riv}$ Water storage in rivers $[\text{mm}]$

$S_y$ Soil water supply $[\text{mm d}^{-1}]$

$W$ Absolute soil water content $[\text{mm d}^{-1}]$

$W_s$ Relative soil moisture $[-]$

Acknowledgments. This study was funded by the Deutsche Forschungsgemeinschaft and the European Commission (ENSEMBLES, GOCE-CT-2003-505539). We thank Wolfgang Cramer, Petra Döll, Holger Hof, Felix Portmann, and Stefan Siebert for in-depth discussions, and Werner von Bloh, Tim Erbrecht, Marlies Gunzenberger, Ursula Heyder, and Christoph Füller for technical support. This study contributes to the implementation of Activity A-3.1 (Water requirements for nature and humans) in the scientific framework of the Global Water System Project (GWSP). Many thanks go to Scott Tyler, Eric Wood, Michiaki Sugita, and two anonymous reviewers for valuable comments on earlier manuscript versions.

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A. Bondeau, D. Gerten, W. Lucht, J. Rohwer, S. Rost, and S. Schaphoff, Climate Impacts and Vulnerabilities Research Domain, Potsdam Institute for Climate Impact Research, Telegrafenberg A62, Potsdam D-14473, Germany. (rost@pik-potsdam.de)