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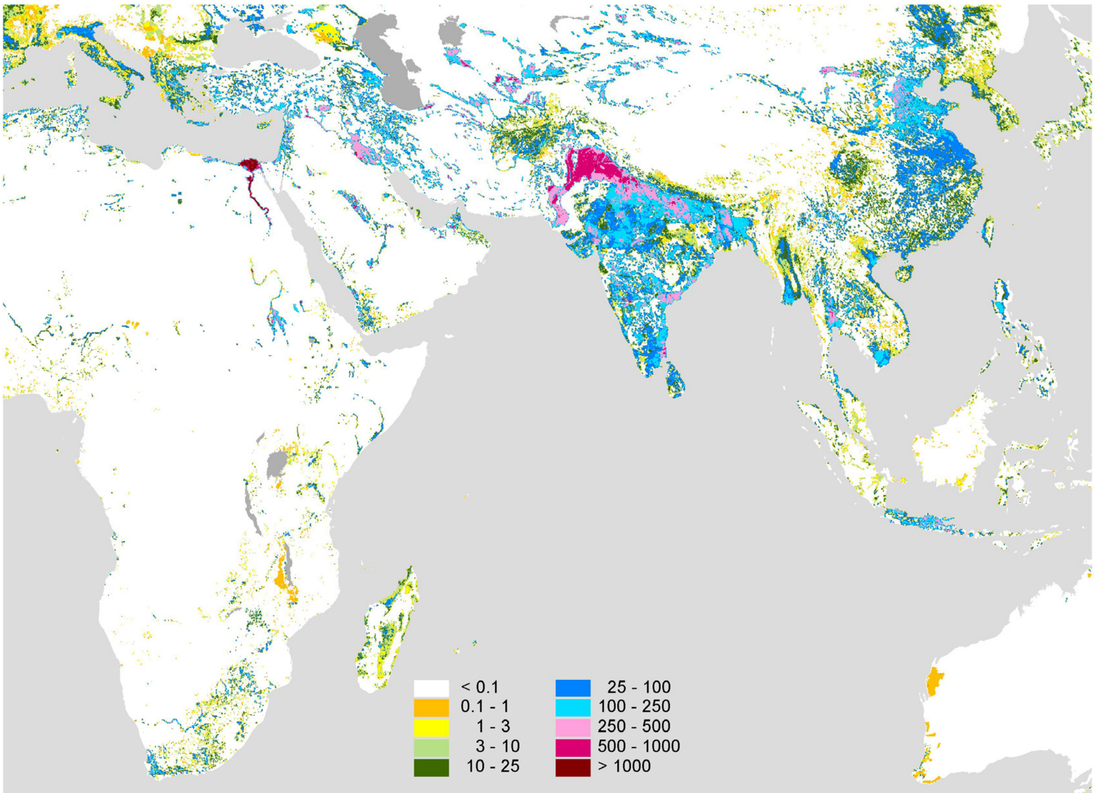
The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops.



RESEARCH REPORT

Stefan Siebert • Petra Döll

March 2008

Frankfurt Hydrology Paper

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The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops

Research report

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Institute of Physical Geography

University of Frankfurt (Main)

March 2008

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Abstract

A new global crop water model was developed to compute blue (irrigation) water requirements and crop evapotranspiration from green (precipitation) water at a spatial resolution of 5 arc minutes by 5 arc minutes for 26 different crop classes. The model is based on soil water balances performed for each crop and each grid cell. For the first time a new global data set was applied consisting of monthly growing areas of irrigated crops and related cropping calendars. Crop water use was computed for irrigated land and the period 1998 – 2002.

In this documentation report the data sets used as model input and methods used in the model calculations are described, followed by a presentation of the first results for blue and green water use at the global scale, for countries and specific crops. Additionally the simulated seasonal distribution of water use on irrigated land is presented. The computed model results are compared to census based statistical information on irrigation water use and to results of another crop water model developed at FAO.

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1 INTRODUCTION

Knowledge about where on earth irrigation occurs and how much water is used for this purpose is an important basis for understanding the role of agriculture for food security or the relevance of agriculture for sustainable water management. About 279 Mha of agricultural land were equipped for irrigation around the year 2000 (Siebert et al., 2006). It was estimated that about 2700 $km^3\ yr^{-1}$ of fresh water is withdrawn from surface water bodies or aquifers to irrigate crops which represents about 70% of the global water withdrawals for agriculture, households and industry (FAO, 2007; Shiklomanov, 2000). Parts of the freshwater withdrawals are return flows that could potentially be reused downstream. The difference between irrigation withdrawal water use (*IWWU*) and return flows, the so called irrigation consumptive water use (*ICWU*), was estimated at 1752 $km^3\ yr^{-1}$ for the year 2000 (Shiklomanov, 2000) which represents more than 90% of the total consumptive water uses in all sectors.

To support sustainable water management, water use is usually compared to available water resources. This allows to compute indicators for water scarcity, sustainability of water resources use or dependency on external resources (e.g. FAO, 2007; Lehner et al., 2006; Alcamo et al., 2003a; Vörösmarty et al., 2000; Seckler et al., 2000; Alcamo et al., 1997). One of the models applied to simulate water resources and water use at the global scale is the WaterGAP model (Alcamo et al., 2003b). The model uses daily time steps on a resolution of 30 arc minutes. It calculates runoff and river discharge as well as water use for irrigation, livestock, manufacturing, cooling of power plants, domestic households and livestock on the other hand. The Global Irrigation Model (GIM), which is the irrigation sub model of WaterGAP, simulates the cropping pattern, cropping intensity and the related irrigation water requirement for rice and the group of non-rice crops (Döll and Siebert, 2002). The model requirements for statistical input data are relatively low to facilitate the model use for analyses of global change scenarios. Using the most recent version 4 of the Digital Global Map of Irrigation Areas (Siebert et al., 2006) as a model input, the global net irrigation water requirement, which is the amount of water needed to ensure optimal growth of irrigated crops, was computed at 1322 $km^3\ yr^{-1}$ for the period 1998 – 2002. The gross irrigation water requirement, which is the water withdrawal from surface or ground water resources assuming optimal growing conditions and specified irrigation efficiencies, was computed at 3008 $km^3\ yr^{-1}$ (Siebert, unpublished).

The inventories of water resources and water uses as mentioned before do not include the so-called virtual water flows (Allan, 1993). Virtual water content of a commodity is defined as the volume of water required to produce the specific commodity. Virtual water flows are induced by trade. If a specific good is imported by country A and exported by country B then the virtual water content of the specific good is also transported from country B to country A and thus a virtual water flow appears from country B to country A. The practical importance of those virtual water flows is that countries poor in water resources can participate in water resources located in water rich countries by importing goods produced in those countries instead of using their own water resources to produce these goods. A water saving can also appear at the global scale namely if the amount of water needed to produce a commodity in the exporting country is lower than the amount of water that would be needed to produce the commodity in the importing country (Oki and Kanae, 2004). In the history, virtual water trade between nations was negligible, in particular for agricultural products, because only very minor portions of food were traded over long distances. But nowadays, in the era of globalization and the related tremendous increase in international trade, virtual water trade is being discussed as an effective instrument to reduce water scarcity and food insecurity (Yang et al, 2006). Therefore, future inventories of water balances for nations or watersheds should also include virtual water flows. It is necessary to distinguish blue and green virtual water flows. Blue water is withdrawn from surface water bodies or ground water while green water is provided by precipitation. The relevancy of both types of virtual water is different. For example, there is competition of the different water use sectors for blue water only.

First estimates quantify the global volume of virtual water flows related to international trade at 1625 km^3 yr^{-1}. About 80% of these virtual water flows relate to the trade in agricultural products, while the remainder is related to industrial product trade (Chapagain and Hoekstra, 2004). Water saving at the global scale by virtual water trade was estimated at 450 km^3 yr^{-1} (Oki and Kanae, 2004), 352 km^3 yr^{-1} (Chapagain et al., 2006) or 337 km^3 yr^{-1} (Yang et al., 2006). However, the uncertainties in the estimates are still very large. Crop water use, for example, was computed in these studies based on climate values averaged for each country. Additionally, blue and green water flows are not given separately which makes it difficult to interpret the specific meaning of the results.

In this study we make a first step towards improving estimates of blue and green virtual water content by presenting a crop water model that simulates requirements of blue and green water for 23 major crops and 3 crop groups in daily time steps. The spatial resolution of the Global Crop Water Model (GCWM) is 5 arc minutes by 5 arc minutes. The final modeling results will be made available to the public via the web site of the virtual water fluxes project at the University of Frankfurt (Main) at http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/Virtual_water/index.html.

In section 2 of this paper we describe the methodology used to develop the model and the input data necessary to use the model. First results for irrigated crops are presented in section 3. In section 4 we compare our results to those of other models and we also discuss limitations and major sources of uncertainties. In section 5 we finally give a summary and draw conclusions.

2 DATA AND METHODS

In this section we describe the input data used by the new model and the methodology to compute crop water uses. The main differences of the new Global Crop Water Model compared to the already existing Global Irrigation Model of WaterGAP are that the cropping pattern and cropping calendar are required as input data set, that the number of crops increased from 2 to 26, that water requirements for irrigated agriculture and water use for rainfed agriculture are computed based on the same methodology which requires also a

TABLE 1

Differences in methodology and input data requirements between the new Global Crop Water Model (GCWM) and the most recent version 2.1f of the WaterGAP model

	GCWM	WaterGAP 2.1f
Blue (irrigation) water requirement of crops	Computed in GCWM based on a soil water balance	Computed in GIM, the irrigation model of WaterGAP (Döll and Siebert, 2002) as the difference between potential evapotranspiration and effective precipitation
Green (precipitation) water use of crops	Computed in GCWM based on a soil water balance	Computed in WGHM, the hydrology model of WaterGAP (Döll et al., 2003) based on a soil water balance
Number of crop classes	26	1 for rainfed agriculture and 2 (rice, nonrice) for irrigated agriculture
Cropping pattern and cropping season	Input from file	Simulated by the models
Method to compute reference evapotranspiration	Penman-Monteith or Priestley-Taylor	Priestley-Taylor
Spatial resolution	5 arc minutes, results can be aggregated to 30 arc minutes	30 arc minutes

calculation of the actual evapotranspiration, that the modeling of water requirements is based on a soil water balance, that two different methods are implemented to compute reference evapotranspiration and that the spatial resolution of the model changed from 30 to 5 arc minutes (Table 1).

2.1 Cropping pattern and cropping season

The data set used to define the cropping pattern and the growing seasons for the 26 crop classes listed in Table 2 is documented in Portmann et al. (2008). The data set refers to the situation around the year 2000 and consists of two parts: monthly grids of growing areas for each of the crop classes with a spatial resolution of 5 arc minutes by 5 arc minutes and a list of cropping calendars for 402 spatial units like countries, federal states, provinces (Figure 1) consistent to the grids of monthly growing areas. The data set explicitly considers multi-cropping practices. By now, it is available for irrigated crops only but data for the related rainfed crops will become available soon.

The list of cropping calendars (for an extract see Figure 2) provides for each crop class and up to five sub-crops the growing area, the month when the growing season starts and the month when the growing season ends. As an example we describe in the following the cropping calendar for the unit California (Figure 2). California has the unit number 840005 that appears in the first column. The crop number is given in the second column and the number of sub-crops in the third column. Beginning with the fourth column total growing area, first month of growing season and last month of growing season are listed for each sub-crop. Thus, the second line can be interpreted as follows: In unit 840005 (California) there are two sub-crops of crop 1 (wheat). The first sub-crop is growing on 98723.06 ha in the period September – June and the second sub-crop is growing on 38363.79 ha in the period April to August. Here the first sub-crop could be irrigated winter wheat while the second sub-crop will be irrigated spring wheat. For the crops sugar cane (12), oil palm (14), citrus (18), date palm (19), grapes (20), cocoa (22), coffee (23), others / perennial (24) and managed grassland / pasture (25) the first month of the growing season will be always January (1) and the last

TABLE 2

Length of crop development stages as fraction of the whole growing period for initial (*L_ini*), crop development (*L_dev*), mid season (*L_mid*) and late season (*L_late*), crop coefficients for initial period (k_c*_ini*), mid season (k_c*_mid*) and at the end of season (k_c*_end*), rooting depth (*rd*) on irrigated and rainfed land and standard crop depletion fraction (p_{std})

Crop	Length of crop development stage (-)				Crop coefficients (-)			Rooting depth *rd* (m)		p_{std} (-)
	L_ini	*L_dev*	*L_mid*	*L_late*	k_c*_ini*	k_c*_mid*	k_c*_end*	Irrigated	Rainfed	
Wheat (1)	0.15	0.25	0.40	0.20	0.40	1.15	0.30	1.25	1.60	0.55
Maize (2)	0.17	0.28	0.33	0.22	0.30	1.20	0.40	1.00	1.60	0.55
Rice (3)	0.17	0.18	0.44	0.21	1.05	1.20	0.75	0.50	1.00	0.00
Barley (4)	0.15	0.25	0.40	0.20	0.30	1.15	0.25	1.00	1.50	0.55
Rye (5)	0.10	0.60	0.20	0.10	0.40	1.15	0.30	1.25	1.60	0.55
Millet (6)	0.14	0.22	0.40	0.24	0.30	1.00	0.30	1.00	1.80	0.55
Sorghum (7)	0.15	0.28	0.33	0.24	0.30	1.10	0.55	1.00	1.80	0.55
Soybeans (8)	0.15	0.20	0.45	0.20	0.40	1.15	0.50	0.60	1.30	0.50
Sunflower (9)	0.19	0.27	0.35	0.19	0.35	1.10	0.25	0.80	1.50	0.45
Potatoes (10)	0.20	0.25	0.35	0.20	0.35	1.15	0.50	0.40	0.60	0.35
Cassava (11)	0.10	0.20	0.43	0.27	0.30	0.95	0.40	0.60	0.90	0.35
Sugar cane (12)	0.00	0.00	1.00	0.00	n.a.	0.90	n.a.	1.20	1.80	0.65
Sugar beets (13)	0.20	0.25	0.35	0.20	0.35	1.20	0.80	0.70	1.20	0.55
Oil palm (14)	0.00	0.00	1.00	0.00	n.a.	1.00	n.a.	0.70	1.10	0.65
Rapeseed / canola (15)	0.30	0.25	0.30	0.15	0.35	1.10	0.35	1.00	1.50	0.60
Groundnuts / Peanuts (16)	0.22	0.28	0.30	0.20	0.40	1.15	0.60	0.50	1.00	0.50
Pulses (17)	0.18	0.27	0.35	0.20	0.45	1.10	0.60	0.55	0.85	0.45
Citrus (18)	0.00	0.00	1.00	0.00	n.a.	0.80	n.a.	1.00	1.30	0.50
Date palm (19)	0.00	0.00	1.00	0.00	n.a.	0.95	n.a.	1.50	2.20	0.50
Grapes / vine (20)	0.30	0.14	0.20	0.36	0.30	0.80	0.30	1.00	1.80	0.40
Cotton (21)	0.17	0.33	0.25	0.25	0.35	1.18	0.60	1.00	1.50	0.65
Cocoa (22)	0.00	0.00	1.00	0.00	n.a.	1.05	n.a.	0.70	1.00	0.30
Coffee (23)	0.00	0.00	1.00	0.00	n.a.	1.00	n.a.	0.90	1.50	0.40
Others (perennial) (24)	0.00	0.00	1.00	0.00	n.a.	0.80	n.a.	0.80	1.20	0.50
Managed grassland/pasture (25)	0.00	0.00	1.00	0.00	n.a.	1.00	n.a.	1.00	1.50	0.55
Others (annual) (26)	0.15	0.25	0.40	0.20	0.40	1.05	0.50	1.00	1.50	0.55

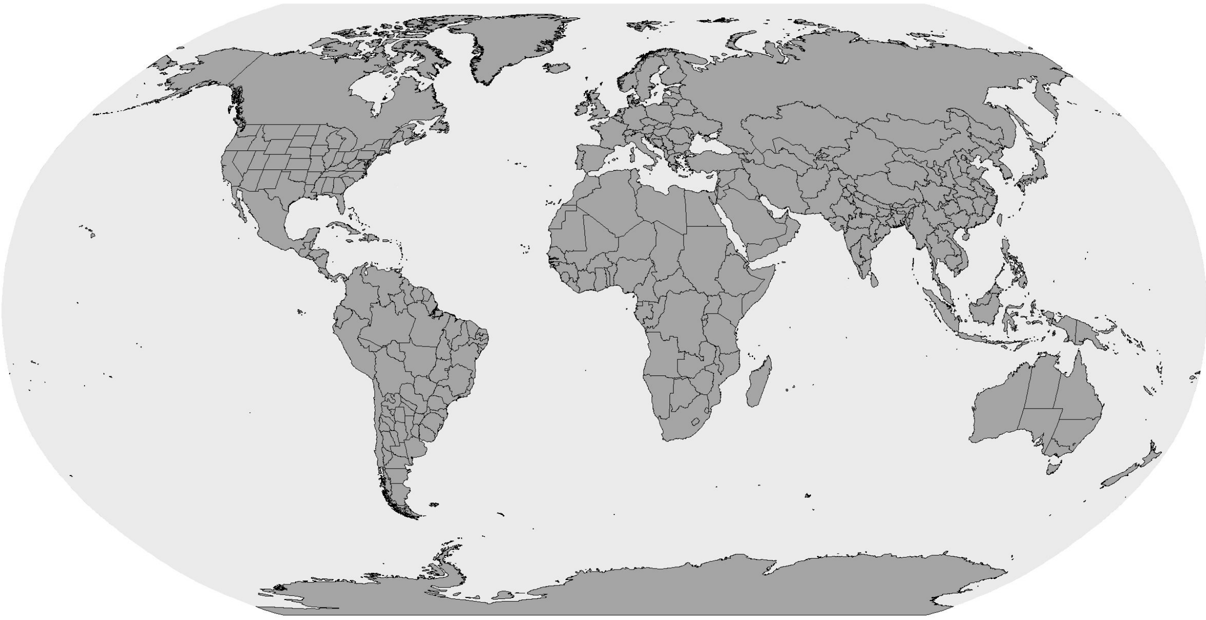
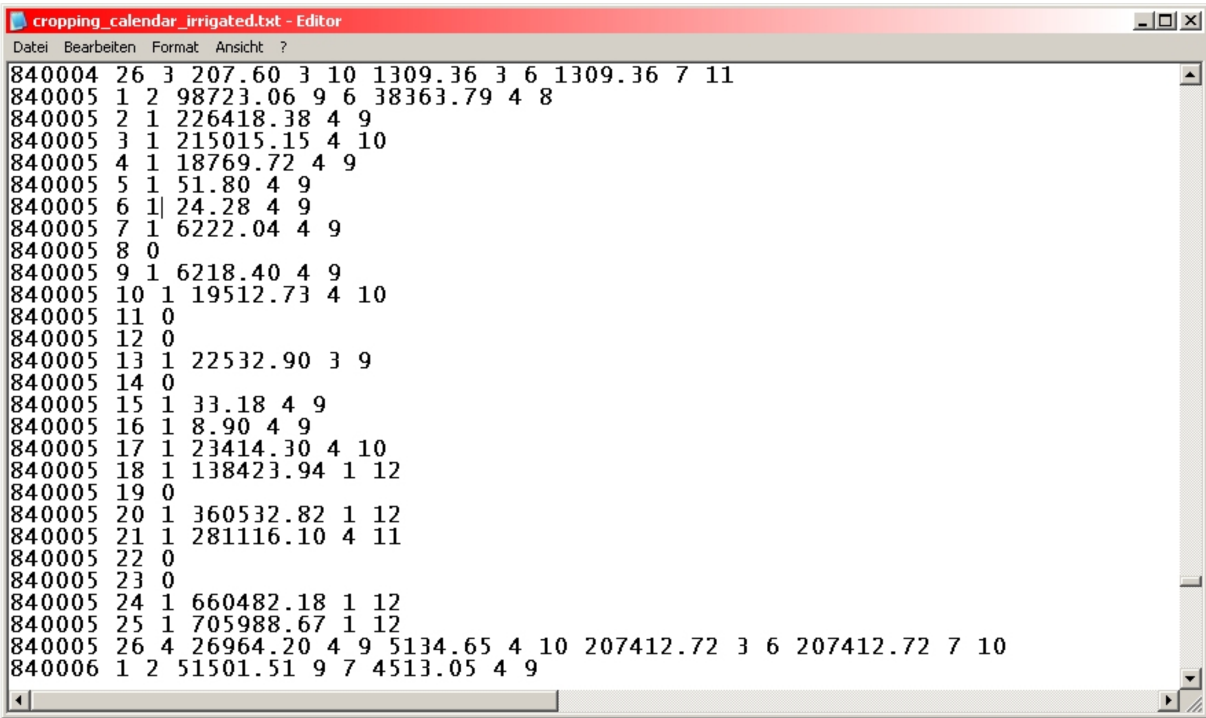


FIGURE 1

Map showing the spatial units for which cropping calendars have been available.




```
840004 26 3 207.60 3 10 1309.36 3 6 1309.36 7 11
840005 1 2 98723.06 9 6 38363.79 4 8
840005 2 1 226418.38 4 9
840005 3 1 215015.15 4 10
840005 4 1 18769.72 4 9
840005 5 1 51.80 4 9
840005 6 1 24.28 4 9
840005 7 1 6222.04 4 9
840005 8 0
840005 9 1 6218.40 4 9
840005 10 1 19512.73 4 10
840005 11 0
840005 12 0
840005 13 1 22532.90 3 9
840005 14 0
840005 15 1 33.18 4 9
840005 16 1 8.90 4 9
840005 17 1 23414.30 4 10
840005 18 1 138423.94 1 12
840005 19 0
840005 20 1 360532.82 1 12
840005 21 1 281116.10 4 11
840005 22 0
840005 23 0
840005 24 1 660482.18 1 12
840005 25 1 705988.67 1 12
840005 26 4 26964.20 4 9 5134.65 4 10 207412.72 3 6 207412.72 7 10
840006 1 2 51501.51 9 7 4513.05 4 9
```

FIGURE 2

Extract from the list of cropping calendars showing the calendar for California (unit 840005).

month will always be December (12). These crops will also never have more than one sub-crop.

Growing areas of sub-crops were defined for each single grid cell by combining the monthly growing areas per crop and grid cell to the cropping calendar of the related spatial unit. Using the monthly growing areas of crops alone is not sufficient to define the cell-specific growing areas of sub-crops because two ore more sub-crops can grow in the same month. However, the cropping calendars for the 402 spatial units are defined in a way that this problem can be solved when using the following two procedures:

a) searching for a month in which only one sub-crop is growing and assigning the monthly growing area to this sub-crop
b) searching for changes in growing areas from month to month and assigning the difference from month to month to the sub-crop that starts or finishes a growing season.

As an example, we show how the cell specific growing area of crop 26 (others annual) can be assigned to the four sub-crops growing in California (see Figure 2). In the first step, we find out that in month 3 (March) only sub-crop 3 is growing. Therefore the monthly growing area of crop 26 can be assigned to crop 26, sub-crop 3 for all grid cells belonging to California. In the second step, we reduce the total monthly growing area in the period March – June (3 – 6) by the growing area of sub-crop 3 in all cells belonging to California. In the third step, we can identify that the change of monthly growing area from June to July is related to the begin of the growing season for sub-crop 4. Therefore, the difference in the remaining monthly growing area between month 7 and month 6 is assigned to sub-crop 4. In the fourth step, the monthly growing area in months 7 – 10 is reduced in all cells belonging to California by the growing area of sub-crop 4. In the fifth step, the remaining growing area in month 10 is assigned to sub-crop 2. Now the monthly growing area in months 4 – 10 is reduced by the growing area of sub-crop 2. Finally, the remaining monthly growing area is assigned to sub-crop 1. This procedure is straight forward and as a result of its application, growing areas and cropping seasons are defined for all the crops and sub-crops in each 5 arc minute grid cell.

2.2 Climate input

Monthly values for precipitation, number of wet days, mean temperature, diurnal temperature range and cloudiness were derived from a time series at a spatial resolution of 30 arc minutes by 30 arc minutes (Mitchell and Jones, 2005). Monthly long-term averages at a resolution of 10 arc minutes by 10 arc minutes for precipitation, number of wet days, diurnal temperature range, sun shine percentage, wind speed and relative humidity were derived from the CRU CL 2.0 data set (New et al., 2002). Daily climate input at 5 arc minute resolution was simulated by computing monthly climate time series at 5 arc minute resolution first and by using these time series thereafter to generate daily time series at this resolution.

Generating monthly climate input at 5 arc minute resolution

Data for relative humidity and wind speed were available as monthly long-term averages for the period 1961-1990 only. Therefore the monthly long-term average (New et al., 2002) was used for each year in the calculation period 1998-2002 and assigned to each of the four 5-minute grid cells contained in the related 10-minute grid cell. Since the wind speed given by New et al. (2002) represented measurements in a height of 10 m, wind speed was converted to represent measurements in 2 m height according to Allen et al. (1999) as follows:

$$u_2\_m = u_{10}\_m \frac{4.87}{\ln 672.58} \tag{1}$$

where u_2_m was the monthly wind speed measured in 2 m height in m s^{-1} and u_{10}_m was the monthly wind speed measured in 10 m height in m s^{-1}. Monthly sunshine percentage was also only available as long-term average (New et al., 2002) while the related time series were given as cloudiness (Mitchell and Jones, 2005). Time series of monthly sunshine percentage were therefore computed by combining the long-term averages at 10 arc minute resolution to the time series of cloudiness at 30 arc minute resolution as:

$$sunp\_m = sunp\_m\_lt\_10 \frac{100 - cld\_m\_30}{100 - cld\_m\_lt\_30} \tag{2}$$

where *sunp_m* was the sunshine percentage (percentage of the maximum possible sunshine) in percent, *sunp_m_lt_10* was the long-term average monthly sunshine percentage at 10 arc minute resolution (New et al., 2002) in percent, *cld_m_30* was the monthly cloudiness at 30 arc minute resolution (Mitchell and Jones, 2005) in percent and *cld_m_lt_30* was the monthly long-term average cloudiness at 30 arc minute resolution computed from (Mitchell and Jones, 2005) for the period 1961-1990 in percent. Values for *sunp_m* were limited to the range from 0 to 100. The monthly sunshine percentage computed that way at a resolution of 10 arc minutes was assigned to each of the four 5-minute grid cells contained in the related 10-minute grid cell. Time series of monthly precipitation and monthly number of wet days were computed as:

$$prec\_m = prec\_m\_30 \frac{prec\_m\_lt\_10}{prec\_m\_lt\_30} \tag{3}$$

and

$$wetd\_m = wetd\_m\_30 \frac{wetd\_m\_lt\_10}{wetd\_m\_lt\_30} \tag{4}$$

where *prec_m* was the monthly precipitation in mm month^{-1}, *prec_m_30* was the monthly precipitation at 30 arc minute resolution (Mitchell and Jones, 2005) in mm month^{-1}, *prec_m_lt_10* was the long-term average monthly precipitation at 10 arc minute resolution (New et al., 2002) in mm month^{-1}, *prec_m_lt_30* was the long-term average monthly precipitation at 30 arc minute resolution computed from New et al. (2002) as average of the nine 10 arc minute cells contained in the 30 arc minute cell in mm month^{-1}, *wetd_m* was the monthly number of wet days, *wetd_m_30* was the monthly number of wet days at 30 arc minute resolution (Mitchell and Jones, 2005), *wetd_m_lt_10* was the long-term average monthly number of wet days at 10 arc minute resolution (New et al., 2002) and *wetd_m_lt_30* was the long-term average monthly number of wet days at 30 arc minute resolution computed from New et al. (2002) as average of the nine 10 arc minute cells contained in the 30 arc minute cell. The monthly precipitation and number of wet days computed that way at a resolution of 10 arc minutes was assigned to each of the four 5-minute grid cells contained in the related 10-minute grid cell. Time series of monthly mean temperature were computed by applying a correction based on the altitude differences between the 5 arc minute cell and its related 30 arc minute cell as:

$$T_{mean}\_m = T_{mean}\_m\_30 + ALR(z\_05 - z\_30) \tag{5}$$

where T_{mean}_m was the monthly mean temperature in the 5 arc minute grid cell in °C, $T\_{mean}\_m\_30$ was the monthly mean temperature in the related 30 arc minute grid cell (Mitchell and Jones, 2005) in °C, *ALR* was the adiabatic lapse rate set to -0.0065 °C m^{-1}, *z_05* was the elevation above sea level in the 5 arc minute grid cell in m and *z_30* was the average elevation above sea level in the related 30 arc minute grid cell in m. The average elevation for the grid cells in 30 arc minute resolution was provided by CRU (Mitchell and Jones, 2005) while the elevation at 5 arc minute resolution was derived from the ETOPO-5 data set (NOAA, 1988) available at: http://www.ngdc.noaa.gov/mgg/global/etopo5.html. Time series of monthly mean daily maximum and minimum temperatures were computed as:

$$T_{max}\_m = T_{mean}\_m + 0.5 dtr\_m \tag{6}$$

and

$$T_{min}\_m = T_{mean}\_m - 0.5 dtr\_m \qquad (7)$$

with

$$dtr\_m = dtr\_m\_30 \frac{dtr\_m\_lt\_10}{dtr\_m\_lt\_30} \qquad (8)$$

where T_{max}_m was the monthly mean daily maximum temperature in the 5 arc minute grid cell in °C, T_{min}_m was the monthly mean daily minimum temperature in the 5 arc minute grid cell in °C, *dtr_m* was the monthly mean diurnal temperature range in °C, *dtr_m_30* was the monthly mean diurnal temperature range in the 30 arc minute cell (Mitchell and Jones, 2005) in °C, *dtr_m_lt_10* was the long-term average monthly diurnal temperature range at 10 arc minute resolution (New et al., 2002) in °C and *dtr_m_lt_30* was the long-term average monthly diurnal temperature range at 30 arc minute resolution in °C computed from New et al. (2002) as average of the nine 10 arc minute cells contained in the 30 arc minute cell.

Generating daily time series of climate input

Daily values of wind speed, sunshine percentage, maximum temperature, minimum temperature and mean temperature were interpolated from monthly values by applying cubic splines (Press et al., 1992). Daily precipitation was simulated by generating a sequence of dry and wet days using the monthly number of wet days (Geng et al., 1986) and distributing monthly precipitation equally over all wet days.

2.3 Reference evapotranspiration (ET_0)

To allow ensemble calculations and to better quantify uncertainties reference evapotranspiration (ET_0) can be simulated in GCWM using the Priestley-Taylor method (Priestley and Taylor, 1972) or using the FAO Penman-Monteith approach (Allen et al., 1998) as:

$$ET_0\_PM = \frac{\Delta}{\Delta + \gamma(1 + 0.33 u_2)}(R_n - G) + \frac{\gamma}{\Delta + \gamma(1 + 0.33 u_2)} \frac{900}{T_{mean} + 273} u_2 (e_s - e_a) \qquad (9)$$

and

$$ET_0\_PT = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \qquad (10)$$

where ET_0_PM was the reference evapotranspiration according to FAO Penman-Monteith in mm day^{-1}, ET_0_PT was the reference evapotranspiration according to Priestley-Taylor in mm day^{-1}, Δ was the slope of the vapor pressure curve in kPa °C^{-1}, γ was the psychrometric constant in kPa °C^{-1}, u_2 was the wind speed at 2 m height in m s^{-1}, R_n was the net radiation at the crop surface in mm day^{-1}, G was soil heat flux in mm day^{-1}, T_{mean} was the daily mean temperature in °C, e_s was the saturation vapor pressure in kPa, e_a was the actual vapor pressure in kPa and α was a dimensionless scaling coefficient. The slope of the vapor pressure curve Δ was computed as:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T_{mean}}{237.3+T_{mean}}\right)\right]}{\left(237.3+T_{mean}\right)^2} \tag{11}$$

and the psychrometric constant γ was computed as:

$$\gamma = \frac{c_p P}{\lambda \varepsilon} \tag{12}$$

where c_p was the specific heat of moist air at constant pressure set to 0.001013 MJ kg^{-1} °C^{-1}, P was atmospheric pressure in kPa, λ was the latent heat of vaporization in MJ kg^{-1} and ε was the ratio of the molecular weight of water vapor to that of dry air set to 0.622. The latent heat of vaporization λ was calculated as:

$$\lambda = 2.501 - 0.002361 T_{mean} \tag{13}$$

and the atmospheric pressure P was computed as:

$$P = 101.3\left(\frac{293-0.0065z}{293}\right)^{5.26} \tag{14}$$

where z was the elevation in m above sea level. The net radiation at the crop surface R_n was the difference between the incoming net shortwave radiation R_{ns} and the outgoing net longwave radiation R_{nl}:

$$R_n = R_{ns} - R_{nl} \tag{15}$$

The net shortwave radiation R_{ns} was computed as:

$$R_{ns} = (1 - albedo) R_s \tag{16}$$

where *albedo* was the canopy reflection coefficient set to 0.23 for the hypothetical grass reference crop and R_s was the incoming shortwave radiation in mm day^{-1} computed as:

$$R_s = \left(a_s + b_s \frac{sunp}{100}\right) R_a \tag{17}$$

where R_a was the extraterrestrial radiation in mm day^{-1} and a_s and b_s were regression constants representing the fraction of extraterrestrial radiation reaching the earth on overcast days (a_s) or the fraction of extraterrestrial radiation reaching the earth on clear days (a_s + b_s). The coefficient a_s was set to 0.25 and the coefficient b_s to 0.50. Extraterrestrial radiation R_a was computed as:

$$R_a = \frac{1}{\lambda}\frac{1440}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \tag{18}$$

where G_{sc} was the solar constant set to 0.082 MJ m^{-2} min^{-1}, ω_s was the sunset hour angle in rad, φ was the latitude in rad, δ was the solar declination in rad and d_r was the inverse relative distance between Earth and Sun computed as:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \tag{19}$$

where J was the number of the actual day in the year between 1 (1st of January) to 365 (31st of December). Because the calculation of solar declination according to Allen et al. (1998) did not work properly for latitudes greater than 55° (N and S), this parameter was computed according to the CBM model of Forsythe et al. (1995) as:

$$\delta = \arcsin[0.39795\cos[0.2163108 + 2\arctan[0.9671396\tan[0.0086(J-186)]]]] \tag{20}$$

The sunset hour angle ω_s was thereafter computed as:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \tag{21}$$

Net outgoing longwave radiation R_{nl} was computed as:

$$R_{nl} = \frac{1}{\lambda}\sigma\left(\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2}\right)\left(0.34 - 0.14\sqrt{e_a}\right)\left(a_c\frac{R_s}{R_{s0}} + b_c\right) \tag{22}$$

where σ was the Stefan-Boltzmann constant set to 4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}, $T_{max,K}$ was the daily maximum temperature in K, $T_{min,K}$ was the daily minimum temperature in K and R_{s0} was the clear-sky radiation in mm day^{-1} computed as:

$$R_{s0} = \frac{1}{\lambda}(a_s + b_s + 0.00002z)R_a \tag{23}$$

According to Shuttleworth (1993) the coefficient a_c was set to 1.35 for arid areas and to 1.00 for humid areas while the coefficient b_c was set to -0.35 for arid areas and to 0.00 for humid areas. A grid cell was defined as arid if the mean monthly relative humidity (*rhum_m*) was less than 60 % in the month with peak evapotranspiration, otherwise the cell was defined to be humid. The actual vapor pressure e_a and the saturation vapor pressure e_s were computed as:

$$e_a = e^0(T_{dew}) = 0.6108\exp\left(\frac{17.27T_{dew}}{237.3 + T_{dew}}\right) \tag{24}$$

and

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2} = 0.5\left[0.6108\exp\left(\frac{17.27T_{max}}{237.3 + T_{max}}\right) + 0.6108\exp\left(\frac{17.27T_{min}}{237.3 + T_{min}}\right)\right] \tag{25}$$

where $e^0(T_{dew})$ was the saturation vapor pressure at dewpoint temperature in kPa, $e^0(T_{max})$ was the saturation vapor pressure at daily maximum temperature in kPa and $e^0(T_{min})$ was the saturation vapor pressure at daily minimum temperature in kPa. Daily dewpoint temperature T_{dew} was estimated as:

$$T_{dew} = \begin{cases} T_{min} & if \quad rhum\_m > 80 \\ T_{min} - 2 & if \quad rhum\_m < 60 \\ T_{min} - 0.1(80 - rhum\_m) & otherwise \end{cases} \quad (26)$$

which means that dewpoint temperature was set to daily minimum temperature for humid conditions, two degrees below daily minimum temperature for arid conditions and to a value in between for cells with a monthly relative humidity larger than 60 % and smaller than 80 %. Daily soil heat flux *G* was estimated according to Shuttleworth (1993) as:

$$G = \frac{1}{\lambda} c_s d_s \left[T_{mean}(day\_n) - T_{mean}(day\_n-1)\right] \quad (27)$$

where c_s was the soil heat capacity set to 2.1 MJ m^{-2} day^{-1} for average moist soil, d_s was the effective soil depth set to 0.18 m, $T_{mean}(day\_n)$ was the daily mean temperature of the actual day in °C and $T_{mean}(day\_n-1)$ was the daily mean temperature of the day before in °C. Following the recommendation of Shuttleworth (1993) the parameter α in the Priestley-Taylor equation (Equation 10) was set to 1.74 for arid grid cells and to 1.26 for humid grid cells.

2.4 Maximum crop evapotranspiration (ET_c)

The maximum daily crop evapotranspiration is the evapotranspiration of a crop that is healthy and well watered. It depends on crop type and on the specific crop development stage and was computed by applying crop coefficients as:

$$ET_c = k_c ET_0 \quad (28)$$

where ET_c is the maximum crop evapotranspiration (mm day^{-1}), k_c the crop coefficient and ET_0 the reference evapotranspiration (mm day^{-1}). The parameters needed to establish the daily crop coefficients (Table 2) were defined according to Allen et al. (1998). Within the initial crop development stage, crop coefficients were constant at the level of k_c_ini. During crop development, crop coefficients increased at constant daily rates to the level given by k_c_mid. In the mid-season period, crop coefficients were constant at the level of k_c_mid and in the late season stage, crop coefficients were assumed to change in constant steps to the value given by k_c_end (Figure 3). For perennial crops the crop coefficient was kept constant at the level of k_c_mid. The total length of the growing season was derived from the cropping calendar and dependent on the specific crop and spatial unit.

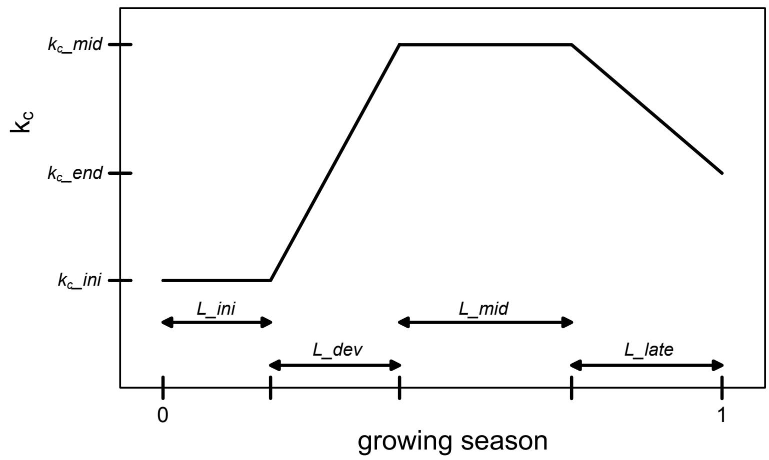


FIGURE 3

Construction of a crop coefficient curve based on parameters listed in Table 2.

2.5 Soil water balances performed to compute actual evapotranspiration (ET_a)

The actual evapotranspiration of crops (ET_a) depends on the available soil moisture and was computed according to Allen et al. (1998) as:

$$ET_a = k_s ET_c \tag{29}$$

with:

$$k_s = \begin{cases} \dfrac{S_t}{(1-p)S_{\max}} & \textit{if} \quad S_t < (1-p)S_{\max} \\ 1 & \textit{otherwise} \end{cases} \tag{30}$$

where ET_a is the actual evapotranspiration (mm day^{-1}), k_s is a dimensionless transpiration reduction factor dependent on available soil water, S_t is the actual available soil water content (mm), S_{max} is the total available soil water capacity (mm) and p is the fraction of S_{max} that a crop can extract from the root zone without suffering water stress. The total available soil water capacity S_{max} was computed by multiplying the total available water capacity in 1 m soil (Batjes, 2006) by the rooting depth rd. The rooting depth is crop specific and varies between irrigated and rainfed crops with lower rooting depth under irrigated conditions. The values used here are documented in Table 2 and were chosen according to Allen et al. (1998). The fraction of the total available soil water that a crop can extract from the root zone without suffering water stress (p) depends on crop type and maximum crop evapotranspiration and was computed according to Allen et al. (1998) as:

$$p = p_{std} + 0.04(5 - ET_c) \tag{31}$$

where p_{std} is a crop specific depletion fraction valid for an evapotranspiration level of about 5 mm day^{-1} derived from Allen et al. (1998) and documented in Table 2. The equation implies that a crop may suffer water stress even at a relatively high soil moisture level if the evaporative power of the atmosphere is high. The soil water balance was computed as:

$$S_{t+1} = S_t + Prec_{t+1} + I_{t+1} - R_{t+1} - ET_a \tag{32}$$

where $Prec$ is the amount of water added to the soil by precipitation (mm day^{-1}), I is the amount of water added to the soil by irrigation (mm day^{-1}) and R is the amount of water going into runoff (mm day^{-1}). For irrigated crops irrigation water was added to the soil if $S_t < (1-p)S_{\max}$ before computing ET_a, so that the water stress coefficient k_s was always 1 and thus ET_a was always ET_c. The amount of irrigation water added to the soil was computed as:

$$I_{t+1} = S_{\max} - S_t \tag{33}$$

and runoff was computed as:

$$R_{t+1} = (Prec_{t+1} + I_{t+1})\left(\frac{S_t}{S_{\max}}\right)^{\gamma_r} \tag{34}$$

Lower values for the parameter γ_r increase runoff and higher values decrease runoff. Since irrigated land is usually flat and in many cases covered with irrigation basins, surface runoff will be lower than on average. Therefore the parameter γ was set to 3 for irrigated land and to 2 for rainfed areas.

Soil water balances were computed for each single sub-crop in each 5 arc-minute grid cell. However, depending on the climate conditions soil water content will also change outside the growing season of irrigated annual crops. To ensure a proper initialization of the soil water storages at the beginning of the growing season it was assumed that on fallow land a crop is growing with a constant k_c of 0.5, a rooting depth of 1 m and a standard depletion fraction p_{std} of 0.55. Please not that the cropping area of this crop was changing depending on the cropping intensity on irrigated land. If the growing season of an irrigated crop was finished, the related crop area was added to the cropping area of the fallow crop and the relative soil water content on fallow land was computed as area weighted average. If a cropping season of an irrigated crop or of a rainfed crop growing in areas equipped for irrigation started, the cropping area of the fallow crop was reduced and the soil water storage of the irrigated crop was initialized using the relative soil water content of the fallow land. The soil water balance on fallow land was computed in the same way than for rainfed crops.

2.6 Crop water use

For irrigated crops fractions of blue and green crop water use were computed while for rainfed crops only green water is used. The amount of green water use of rainfed crops is equal to the amount of simulated actual evapotranspiration (ET_a). Similar to FAO (2005) two different soil water balances were performed for irrigated crops:

a) one soil water balance was carried out using all the crop parameters of irrigated crops (e.g. rooting depth) but assuming that the soil ***is not*** receiving any irrigation water and
b) one soil water balance was carried out with the same crop parameters but assuming that the soil ***is*** receiving irrigation water.

The green water use of irrigated crops in then the actual evapotranspiration (ET_a) computed using soil water balance (a) while the blue water requirement of irrigated crops was computed as difference between ET_a on soil (b) and ET_a on soil (a).

2.7 Evapotranspiration on days with snow covered or frozen soil

Where the soil is snow covered or frozen vegetation will not contribute to ET_c and evapotranspiration will mainly depend on the availability of free water at the surface and on the albedo of the surface (Allen et al., 1998). For those days ET_c was computed as a function of solar radiation R_s:

$$ET_c = 0.2R_s \tag{35}$$

A simple snow model was run to decide whether the surface is snow covered or not. If the daily mean temperature was below 0°C all precipitation was assumed to fall as snow and the related amount of precipitation water was added to a snow water storage instead of to the soil. On days with a snow water storage larger than 0, ET_c reduced the snow water storage and was not reducing the soil water storage. If the daily mean temperature was larger than 0°C and the snow water storage was larger than 0 mm, snow melt was computed as:

$$snow\_melt = T_{mean} * ddf \tag{36}$$

where the day degree factor *ddf* set to 4 mm °C^{-1}. Snow melting reduced the snow water storage and increased the amount of daily precipitation entering the soil.

2.8 Application of the model for irrigated crops and the period 1998 – 2002

The model was applied for irrigated crops and the period 1998 – 2002. As soon as monthly growing areas and cropping calendars for rainfed crops are available, the model will also be applied for rainfed crops. While the climate input consisted of time series, land cover was kept constant. To allow a proper initialization of the soil water storages the simulations were started already with year 1997. The results presented in the following were computed using the FAO Penman-Monteith equation to compute the evapotranspiration.

3 RESULTS

The mean annual blue (irrigation) water requirement computed by the GCWM was 1181 km^3 for the period 1998 – 2002. The related green (precipitation) water use of crops on irrigated land was 919 km^3 yr^{-1}. Thus the computed blue water requirement accounts for 56.2 % of the global crop water use on irrigated land. Since the total harvested area of irrigated crops was about 312 Mha (Portmann et al., 2008), the blue water requirement was 378 mm yr^{-1} on average related to the harvested crop area.

Irrigation water requirements per 30 arc minute cell are shown in Figure 4a. Near the equator one 30 arc minute by 30 arc minute cell covers an area of about 2400 km^2. In Figure 4a high irrigation requirements appear for areas with a high density of irrigated areas, a high cropping intensity on irrigated land and additionally a large climatic water deficit during the growing season. Those areas were for example located in the Punjab region in Pakistan and India, the Nile delta in Egypt and in parts of California. Irrigation water requirements were more than 1000 mm yr^{-1} in grid cells belonging to these regions. Irrigation water requirements related to the actually used irrigated area of the 30 arc minute grid cells are shown in Figure 4b. In this representation, the absolute values of water use are independent of the density of irrigated areas in the grid cell. High values of more than 1000 mm yr^{-1} were found for all arid regions on the globe, e.g. the Western United States, North-East Brazil, along the west coast of South America, in the Near East region, South Asia, Australia and the non-tropical regions of Africa. The percentage of crop evapotranspiration on irrigated land met by blue water (Figure 4c) shows a typical gradient from less than 10 % in temperate, humid regions (e.g. Scandinavia, Alaska) to 10 – 30 % in Central Europe, the Eastern United States and Southern China, 30 – 60 % in regions like Northern Spain, Northern Italy or along the East coast of Australia and more than 60 % in semi-arid and arid regions.

The largest crop-specific irrigation water requirements were simulated for rice (308 km^3 yr^{-1}), wheat (208 km^3 yr^{-1}), managed grassland (90 km^3 yr^{-1}), maize (84 km^3 yr^{-1}), other perennial crops (84 km^3 yr^{-1}) and cotton (83 km^3 yr^{-1}). These are also the crops that have the largest harvested areas on irrigated land (Table 3). For rice, irrigation water requirements (related to the total 30 arc minute grid cell area) of more than 100 mm yr^{-1} were computed for the Ganges, Brahmaputra and Indus basins in India, Bangladesh and Pakistan, the Eastern part of China, the island of Java (Indonesia), the Nile delta in Egypt and the lower Mississippi in the United States (Figure 5a). For wheat, the largest irrigation water requirements on that scale were computed for the Indus basin, the whole North-Western part of India and along the Nile river in Egypt (Figure 5b). The irrigation water requirements for maize were largest for the Great Plains in the United States, along the Nile river in Egypt and for the coastal plain southeast of Peking in China (Figure 5c). The global average of the irrigation water requirement related to the harvested area of the crop was largest for date palms (1428 mm yr^{-1}), managed grassland (771 mm yr^{-1}) and sugar cane (673 mm yr^{-1}). The percentage of crop water use provided as irrigation water was largest for date palms (89 %) and sugar beets (75 %). Low percentages of crop water use provided as irrigation water were computed for cocoa and oil palms (Table 3) which indicates that these crops are growing in more humid

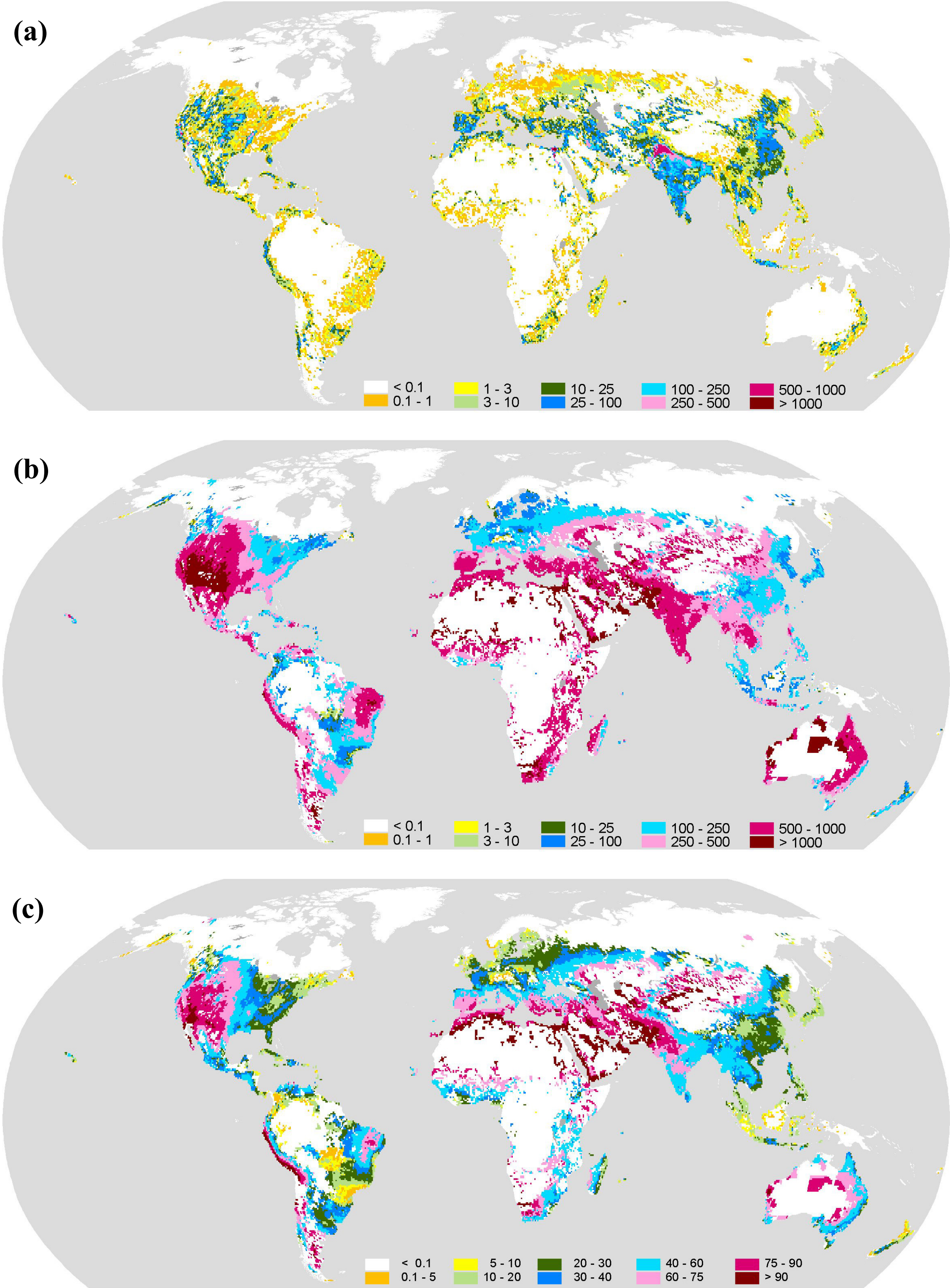


FIGURE 4

Mean blue water requirement during period 1998 – 2002 related to total cell area of 30 arc minute cells in mm yr^{-1} (a), mean blue water requirement during period 1998 – 2002 related to the used irrigated area of 30 arc minute cells in mm yr^{-1} (b) and percentage of total crop evapotranspiration on irrigated cropland from blue (irrigation) water (c).

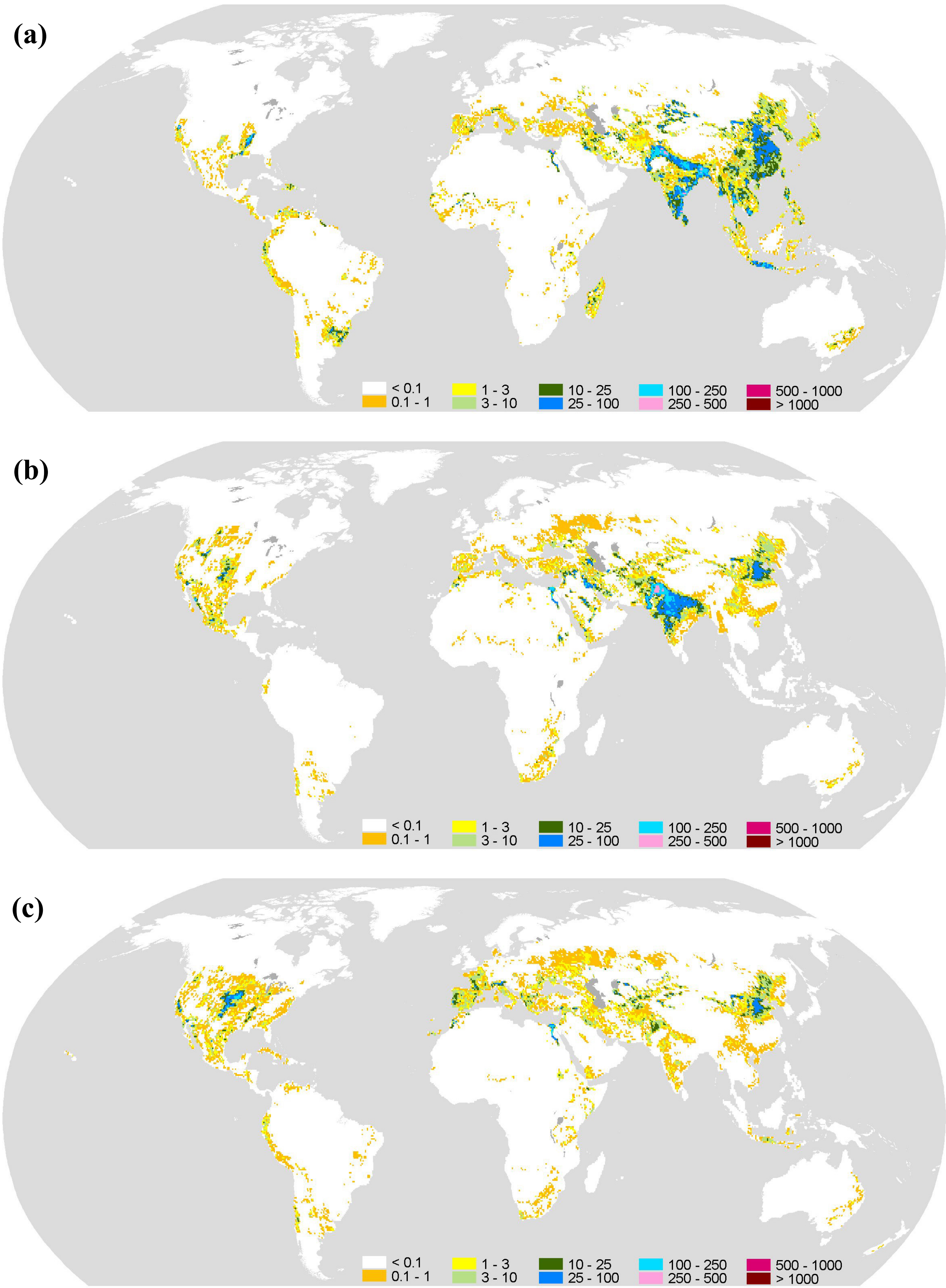


FIGURE 5

Mean blue water requirement during period 1998 – 2002 related to total cell area of 30 arc minute cells in mm yr^{-1} for rice (a), wheat (b) and maize(c).

regions or that irrigation water is only required to balance out water deficits in a relatively short part of the growing season.

At the global scale, the largest blue water requirements of crops were computed for the months July and August. The two months accounted for about 25 % of the total irrigation water requirements (Figure 6). However, the seasonality of irrigation water requirements depends on the specific crop and the location of the growing area of the crop, mainly its

TABLE 3

Irrigated area harvested (*IAH*) in ha yr^{-1}, total irrigation water requirement (*IWR_{tot}*) in km^3 yr^{-1}, crop water use from green water (*CWU_{green}*) in km^3 yr^{-1}, irrigation water requirement related to *IAH* (*IWR_{IAH}*) in mm yr^{-1} and percentage of crop evapotranspiration from irrigation water (*IWR_{frac}*) computed for irrigated land by using the Global Crop Water Model (GCWM) in the period 1998 – 2002.

Crop	*IAH** (ha yr^{-1})	IWR_{tot} (km^3 yr^{-1})	CWU_{green} (km^3 yr^{-1})	IWR_{IAH} (mm yr^{-1})	IWR_{frac} (%)
Wheat	66,632,207	207.9	115.4	312	64
Maize	29,900,725	84.2	98.1	282	46
Rice	103,119,735	307.8	337.1	298	48
Barley	4,645,845	10.9	8.5	234	56
Rye	442,272	1.0	1.2	232	45
Millet	1,743,732	4.0	4.3	227	48
Sorghum	3,436,564	10.8	10.0	313	52
Soybeans	6,032,662	17.3	25.0	287	41
Sunflower	1,268,735	4.1	3.5	322	54
Potatoes	3,745,495	13.3	8.5	356	61
Cassava	11,194	0.0	0.0	273	48
Sugar cane	10,189,040	68.6	70.9	673	49
Sugar beets	1,574,017	9.1	3.0	575	75
Oil palm	11,000	0.0	0.1	435	32
Rapeseed / canola	3,403,812	7.9	3.0	231	73
Groundnuts / peanuts	3,675,801	7.5	13.1	204	36
Pulses	5,455,809	22.4	7.7	411	75
Citrus	3,562,670	22.6	17.8	634	56
Date palm	723,436	10.3	1.3	1428	89
Grapes / vine	1,726,682	7.0	5.0	407	58
Cotton	16,252,239	82.9	46.8	510	64
Cocoa	12,544	0.0	0.1	258	20
Coffee	173,916	1.1	1.4	643	44
Others (perennial)	12,852,976	84.2	55.9	655	60
Managed grassland / pasture	11,684,004	90.1	47.0	771	66
Others (annual)	20,138,732	62.2	34.2	309	65
Fallow**	n.a.	43.2	0.0	n.a.	n.a.
Total	312,431,073	1181.525	915.737	378	56

*: It was assumed that perennial crops, sugar cane and grassland / pasture are harvested once in a year.

**: In the fallow or rainfed period after the harvesting irrigated crops there is still blue water stored in the soil which can go into evapotranspiration. Since the specific crop rotation within the grid cells is unknown, evapotranspiration of blue water in the rainfed period cannot be attributed to a specific crop and appears therefore summarized in the fallow category.

latitude (Figures B3 – B5 in the appendix). The largest irrigation water requirements for wheat were computed for the months March and April, while for rice the largest irrigation water requirement were simulated for the period June – September. Compared to wheat, the irrigation water use for rice was found to be much more balanced between the different months (Figure 6).

The largest irrigation water requirements at the country scale were computed for India (287 km^3 yr^{-1}), China (147 km^3 yr^{-1}), the United States (139 km^3 yr^{-1}) and Pakistan (117 km^3 yr^{-1}). These countries account for 58 % of the global irrigation water requirements (Table A1 in the appendix). Irrigation water requirements of more than 1 km^3 yr^{-1} were simulated for 59 countries. The largest irrigation requirements related to the irrigated area harvested were calculated for the Arabian countries United Arab Emirates (1616 mm yr^{-1}), Oman (1461 mm yr^{-1}), Bahrain (1272 mm yr^{-1}), Saudi Arabia (967 mm yr^{-1}), Qatar (879 mm yr^{-1}) and Kuwait (858 mm yr^{-1}), for the North-African countries Mauritania (864 mm yr^{-1}), Libya (847 mm yr^{-1}), Sudan (836 mm yr^{-1}) and Egypt (779 mm yr^{-1}) and for the Near East countries Iraq (855 mm yr^{-1}), Israel (835 mm yr^{-1}) and Jordan (775 mm yr^{-1}). The lowest irrigation water requirements related to irrigated area harvested were computed for small islands like Northern Marianna Islands and Guam (0 mm yr^{-1}), but also for some European countries like Switzerland (6 mm yr^{-1}), Denmark (23 mm yr^{-1}) and Ireland (41 mm yr^{-1}). The fraction of total crop water use required as blue water was largest for Egypt and the Arabian countries Bahrain, United Arab Emirates, Qatar, Oman, Saudi Arabia and Kuwait (for all larger than 93 %). For 39 countries the blue water requirement was larger than 70 % of the total crop water use on irrigated land. On the other hand the percentage of green water use was larger than 70 % for 58 countries indicating the importance of stored precipitation water even on irrigated land.

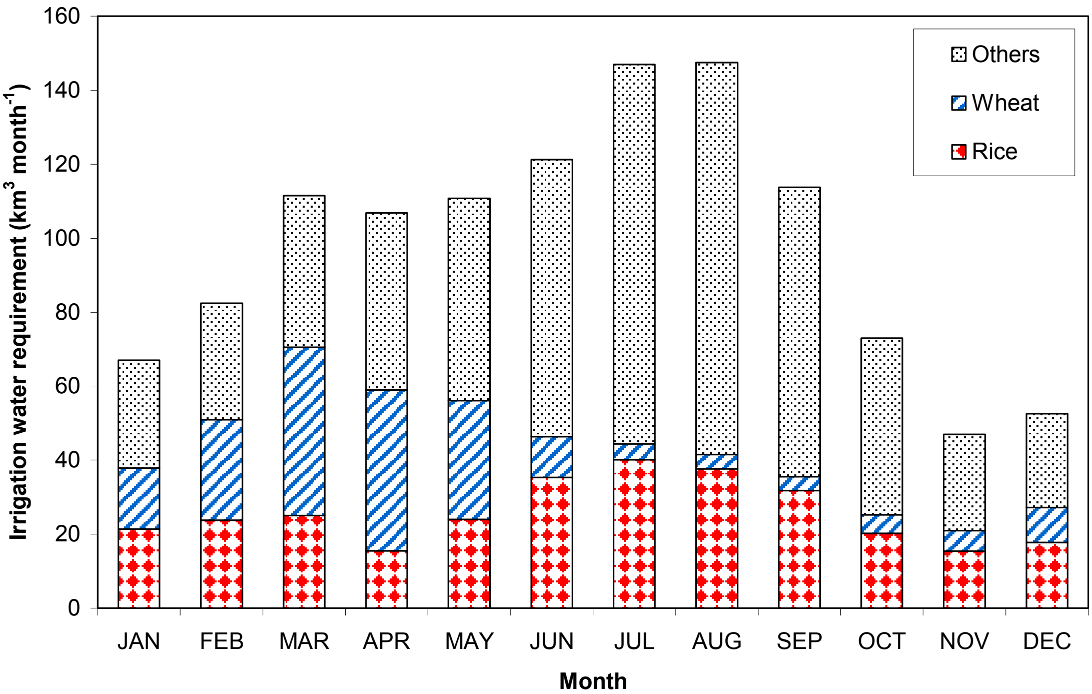


FIGURE 6

Mean monthly blue water requirements during period 1998 – 2002 for rice, wheat and the other crops in km^3 $month^{-1}$.

4 DISCUSSION

The model presented here should be considered as a first attempt to simulate green and blue water use on cropland. It is necessary to analyze the uncertainty of the model and to check the sensitivity to changes of the most important parameters in a systematic way. Several sources of uncertainty were already identified. These are:

- the data set on monthly crop growing areas and the related cropping calendars
- the parameters used to compute daily crop coefficients (k_c)
- the methodology to compute reference evapotranspiration and
- the spatial and temporal resolution of the used climate input data.

A systematic uncertainty analysis of the model will be the objective of further research. Here we present first results of a comparison of model results to statistical information and to results of other models.

4.1 Comparison of the simulated irrigation water requirements to census-based statistical information

The interpretation of a comparison of simulated results for irrigation water requirement to census-based statistical information is difficult because published statistics usually refer to irrigation water withdrawals. These withdrawals are larger than the crop water requirements because a significant part of the water withdrawn from its source goes into unproductive losses (e.g. evaporation and leakage in canals on the way to the field, percolation losses in the field). On the other hand the irrigation water requirements computed by the model refer to the amount of water that would potentially be needed to ensure optimal plant growing. In many cases farmers decide because of several reasons (e.g. water shortages, high costs for water, electricity and labour, damaged infrastructure, labour peaks) to provide a lower amount of water to the plants and to practice so called deficit irrigation. These limitations have to be taken into account when interpreting the comparisons in the following two sections to data on irrigation water withdrawals for European countries and to consumptive water uses in the federal states of the United States of America. Because of the well established quality standards in the statistical reporting system in the European Union and the United States these two sources of information are assumed to be relatively reliable compared to statistics in other countries.

Comparison of model results to statistics on irrigation withdrawal water use in European countries

The statistics used here were collected by EUROSTAT from national sources and refer to total annual surface and groundwater abstraction of agriculture for irrigation purposes (EUROSTAT, 2007). We computed averages for the years 1998 – 2002 if data were available for these years (Table 4). In some cases however, we had to consider older statistics because of missing data. Therefore the reference years for the statistics are also listed. The comparison shows that the computed irrigation water requirements are lower than the reported withdrawals and reasonable for most of the countries that reported large irrigation water uses, e.g. Turkey, Spain, Greece, Portugal, Bulgaria, Germany, Netherlands and Denmark. But also for some countries, which reported low irrigation water withdrawals, the computed results were in the expected range, e.g. for Sweden, Austria, Finland and Lithuania. GCWM simulated too high irrigation water requirements for Romania, Hungary, England and Wales, Poland, Slovakia, the Czech Republic and Slovenia while it simulated to less irrigation water requirements for Norway. The differences for the Eastern European countries maybe explained by incorrect model inputs related to irrigated areas and irrigated crops. It was already mentioned elsewhere (Siebert et al., 2006) that the data on irrigated area for these countries are uncertain because of the ongoing restructuring of the irrigation sector. Additionally, it was also reported, that actual water withdrawals for irrigation are much lower than the requirements (e.g. for Romania in Nicolaescu et al., 2005). The differences for Norway were surprising because the results for the other Scandinavian countries fitted well to the expected irrigation water requirements based on the statistics. Thus there is a need for further investigations to find the reasons for it.

TABLE 4

Reference years of the statistics and of the model output, irrigation withdrawal use (IWU) reported by the EUROSTAT statistics in $Mm^3\ yr^{-1}$ and irrigation water requirement (IWR) as simulated by the Global Crop Water Model (GCWM) in $Mm^3\ yr^{-1}$ and the ratio between the simulated IWR and IWU.

Country	Reference year(s) EUROSTAT	Reference year(s) GCWM	IWU EUROSTAT ($Mm^3\ yr^{-1}$)	IWR GCWM ($Mm^3\ yr^{-1}$)	IWR / IWU (-)
Turkey	1997 - 2001	1998 - 2002	28,480.8	14,628.7	0.51
Spain	1998 - 2002	1998 - 2002	22,530.6	18,631.1	0.83
Greece	1997	1998 - 2002	7,600.0	6,930.4	0.91
Portugal	1998	1998	6,550.9	3,269.6	0.50
Romania	1998 - 2002	1998 - 2002	574.8	900.3	1.57
Bulgaria	1998 - 2002	1998 - 2002	486.6	120.8	0.25
Germany	1998, 2002	1998, 2002	152.7	146.3	0.96
Netherlands	1995 - 1999	1998 - 2002	141.8	123.4	0.87
Denmark	1995	1998 - 2002	140.0	47.3	0.34
Norway	1998 - 2002	1998 - 2002	129.3	15.1	0.12
Hungary	1998 - 2002	1998 - 2002	121.6	206.1	1.69
England and Wales	1997 - 2001	1998 - 2002	119.7	214.1	1.79
Sweden	1998 - 2002	1998 - 2002	101.8	47.9	0.47
Poland	1998 - 2002	1998 - 2002	97.2	103.8	1.07
Austria	1995 - 1999	1998 - 2002	66.4	34.6	0.52
Slovakia	1998 - 2002	1998 - 2002	47.9	191.2	3.99
Finland	1999	1999	40.0	19.4	0.49
Czech Republic	1998 - 2002	1998 - 2002	8.1	20.6	2.55
Lithuania	2003	1998 - 2002	6.6	3.1	0.48
Slovenia	1995, 2002	1998 - 2002	5.7	5.6	0.99
Luxembourg	1995	1998 - 2002	0.2	< 0.1	0.09

Comparison of model results to statistics on irrigation consumptive water use in the United States of America

The computed irrigation water requirements were compared to published information on irrigation consumptive use (Hutson et al., 2004; Solley et al., 1998) on the level of the federal states. Because the water census undertaken in year 2000 (Hutson et al., 2004) only collected data on irrigation withdrawal uses, irrigation consumptive use was computed for each federal state by applying the ratio between irrigation consumptive use and irrigation withdrawal use published for the water census 1995 (Solley et al., 1998). It was found, that there is in general a reasonable agreement between the values computed by the GCWM and the published census data (Figure 7). On the level of federal states the two data sets were correlated with a r^2 of 0.85, the modeling efficiency according to Nash and Sutcliffe (1970) was 0.82. In general, computed irrigation water requirements were larger than reported water consumption for all the states in the centre of the country (Texas, Louisiana, New Mexico, Oklahoma, Arkansas, Kansas, Nebraska, Colorado). A first analysis indicated that the large wind speeds reported for this area caused a relatively high reference evapotranspiration computed using the Penman-Monteith approach while the differences became much lower when using the Priestley-Taylor equation to compute ET_0 (r^2 of 0.94, Nash-Sutcliffe coefficient 0.93). The irrigation water requirement computed by the GCWM for the total United States and year 2000 (147.8 km^3 yr^{-1}) was also larger than the reported consumptive water use of 117.3 km^3 yr^{-1}. Further research is therefore needed to identify the specific reasons for the differences.

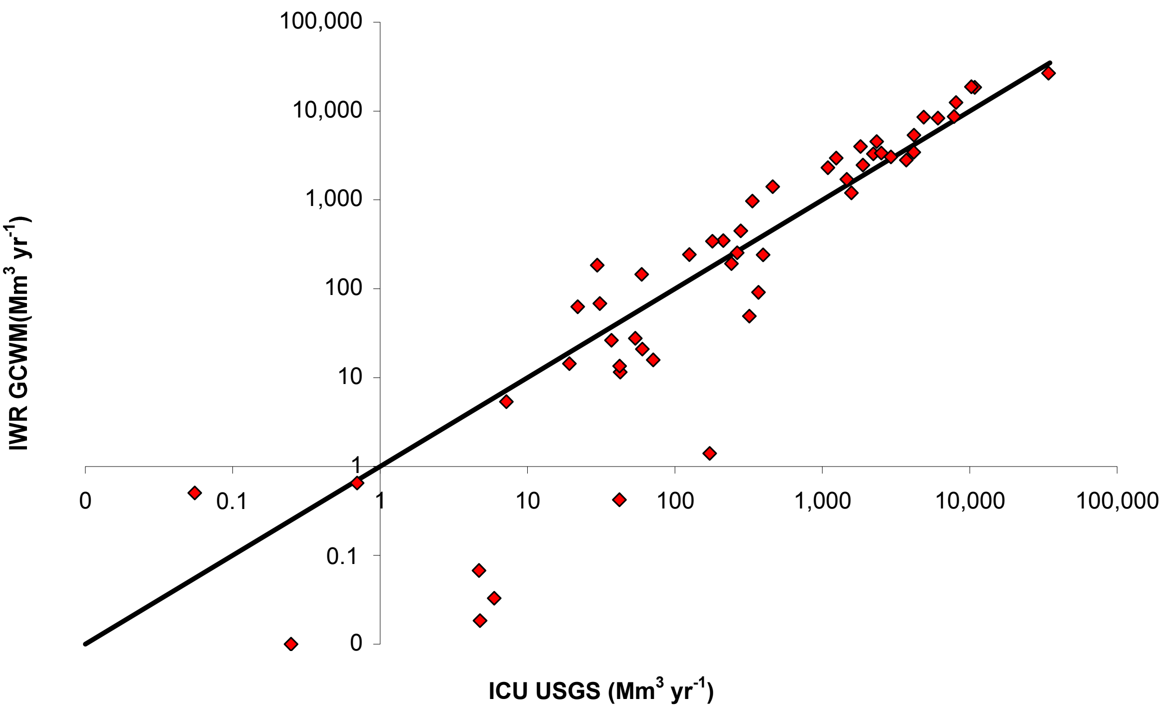


FIGURE 7

Irrigation consumptive water use according to the USGS statistics (ICU USGS) and irrigation water requirements computed by the Global Crop Water Model (GCWM) for the reference year 2000 in federal states of the United States in Mm^3 yr^{-1}.

4.2 Comparison of the simulated irrigation water requirements to agricultural water use and irrigation water requirement reported by FAO for 90 developing countries

In the following section we compare the irrigation water requirements modeled using the GCWM to those modeled by the Food and Agriculture Organization of the United Nations (FAO) and to total agricultural water withdrawals reported in the FAO AQUASTAT database. The FAO used a crop water model that is also based on a soil water balance and the mean climate 1961-90 (New et al., 1999) as climate input (FAO, 2005). The land use was based on a previous version of the Digital Global Irrigation Map (Siebert et al., 2001) and cropping calendars from an earlier version of the FAO AQUASTAT database. The total irrigation water requirement of the 90 developing countries computed by FAO was 824 km^3 yr^{-1}, while the corresponding irrigation water requirement of GCWM was 902 km^3 yr^{-1}. It was found that the irrigation water requirements simulated by GCWM were larger for many arid countries (Table 5). For countries, in which rice is the dominating irrigated crop, FAO computed larger values (e.g. for Indonesia, Vietnam, Myanmar, Philippines). The reason maybe that FAO assumed for rice cultivation an additional irrigation water requirement of 250 mm at the beginning of the growing season to flood the paddy fields (FAO, 2005).

TABLE 5

Agricultural water withdrawal use (*AWWU*) in km^3 yr^{-1}, irrigation water requirement as computed by FAO (IWR_{FAO}) and by the Global Crop Water Model (IWR_{GCWM}) in km^3 yr^{-1}, ratio between IWR_{GCWM} and *AWWU* (only developing countries with an *AWWU* of more than 4 km^3 yr^{-1} are shown in the table).

Country	*AWWU* (km^3 yr^{-1})	IWR_{FAO} (km^3 yr^{-1})	IWR_{GCWM} (km^3 yr^{-1})	IWR_{GCWM} / *AWWU* (-)
India	558.00	303.24	286.97	0.51
China	427.00	153.90	147.22	0.34
Pakistan	163.00	72.14	117.04	0.72
Thailand	82.80	24.83	19.09	0.23
Bangladesh	76.40	19.09	18.67	0.24
Indonesia	75.60	21.49	13.58	0.18
Iran, Islamic Rep of	66.20	21.06	40.78	0.62
Mexico	60.30	18.53	26.80	0.44
Egypt	59.00	28.43	46.92	0.80
Viet Nam	48.60	15.18	7.41	0.15
Iraq	39.40	11.20	20.86	0.53
Brazil	36.60	6.21	8.34	0.23
Sudan	36.10	14.43	10.09	0.28
Myanmar	32.60	9.79	5.92	0.18
Turkey	27.90	11.27	14.63	0.52
Afghanistan	22.80	8.78	9.44	0.41
Argentina	21.50	3.43	5.75	0.27
Philippines	21.10	6.33	3.80	0.18
Syrian Arab Republic	18.90	8.52	9.46	0.50

Country	$AWWU$ ($km^3\ yr^{-1}$)	IWR_{FAO} ($km^3\ yr^{-1}$)	IWR_{GCWM} ($km^3\ yr^{-1}$)	$IWR_{GCWM} / AWWU$ (-)
Peru	16.40	5.07	5.07	0.31
Saudi Arabia	15.40	6.68	12.38	0.80
Madagascar	14.30	3.58	2.81	0.20
Ecuador	14.00	2.67	2.72	0.19
Sri Lanka	12.00	2.92	2.22	0.19
Morocco	11.00	4.28	8.97	0.82
Nepal	9.82	2.45	4.20	0.43
Korea, Republic of	8.92	2.67	0.84	0.09
Chile	7.97	1.59	3.00	0.38
South Africa	7.84	2.34	8.81	1.12
Yemen	6.32	2.53	2.93	0.46
Mali	5.90	2.06	1.27	0.21
Cuba	5.64	1.41	1.62	0.29
Malaysia	5.60	1.68	0.62	0.11
Nigeria	5.51	1.65	0.89	0.16
Ethiopia	5.20	0.56	1.19	0.23
Korea, Dem. Rep.	4.96	1.49	1.10	0.22
Colombia	4.92	1.23	0.96	0.20
Tanzania	4.63	0.56	0.98	0.21
Cambodia	4.00	1.20	1.04	0.26
All 90 countries	2101.12	824.21	902.02	0.43

5 SUMMARY AND CONCLUSIONS

The presented global crop water model was developed to compute blue (irrigation) water requirements and crop evapotranspiration from green (precipitation) water at a spatial resolution of 5 arc minutes by 5 arc minutes for 26 different crops. The model is based on soil water balances performed for each crop and each grid cell. For the first time a new global data set was applied consisting of monthly growing areas for these 26 crops and related cropping calendars. Crop water use was computed for the period 1998 – 2002.

First results for irrigated cropland are presented in this report. The global irrigation water requirement in the reference period was 1181 $km^3\ yr^{-1}$ while the green water use of irrigated crops was 919 $km^3\ yr^{-1}$. At the global scale the largest irrigation water requirement was computed for rice, wheat, managed grassland, maize and sugar cane. The percentage of crop water use provided as irrigation water was largest for date palms and sugar beets while for cocoa and oil palms green water use was dominant. The countries with the largest irrigation water requirements were India, China, the United States and Pakistan. A strong seasonal variation of irrigation water requirements was observed with maximum monthly values for July and August.

A comparison of the model results for irrigated crops to external statistical information and to results of other models showed a reasonable agreement for most countries in Europe, many of the federal states in the US and the most developing countries. These first comparisons clearly indicated the need for a systematic validation of the model including an uncertainty and sensitivity analysis.

As soon as the data set of monthly crop growing areas also includes rainfed crops, the model will be applied to compute the green water use of rainfed crops to provide consistent figures for the whole crop water use. The modeling results will be made available to the public via the web site of the "virtual water project" at http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/Virtual_water/index.html.

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. & Siebert, S. (2003a): Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. Hydrological Sciences Journal, 48(3), 339-348.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. & Siebert, S. (2003b): Development and testing of the WaterGAP 2 global model of water use and availability. Hydrological Sciences Journal, 48(3), 317-338.

Alcamo, J., Döll, P., Kaspar, F. & Siebert, S. (1997): Global change and global scenarios of water use and availability: An application of WaterGAP 1.0, Report A9701, Center for Environmental Systems Research, University of Kassel, Germany, 47 pp + Appendix.

Allan, J.A. (1993) 'Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible' In: Priorities for water resources allocation and management, ODA, London, pp. 13-26.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998): Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, Rome, Italy.

Batjes, N. H. (2006): ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid. Report 2006/02 (available through http://www.isric.org), ISRIC – World Soil Information, Wageningen, The Netherlands, (with data set).

Chapagain, A. K. & Hoekstra, A. Y. (2004): Water footprints of nations. Value of Water Research Report Series No. 16, UNESCO-IHE, Delft, The Netherlands.

Chapagain, A.K., Hoekstra, A.Y., & Savenije, H.H.G. (2006): Water saving through international trade of agricultural products. Hydrology and Earth System Sciences 10 (3), 455-468.

Döll, P., Kaspar, F. & Lehner, B. (2003): A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology, 270 (1-2), 105-134.

Döll, P. & Siebert, S. (2002): Global modeling of irrigation water requirements. Water Resources Research, 38(4), 8.1-8.10, DOI 10.1029/2001WR000355.

EUROSTAT (2007): Annual water abstraction by source and by sector. Online database, available at: http://epp.eurostat.ec.europa.eu/portal/page?_pageid=1073,46870091&_dad=portal&_schema=PORTAL&p_product_code=ENV_WATQ2_1.

FAO (2007): AQUASTAT data base. FAO, Rome, Italy, available at: http://www.fao.org/ag/agl/aglw/aquastat/main/index.stm.

FAO (2005): Review of agricultural water use per country. Online publication, FAO, Rome, Italy, available at: http://www.fao.org/ag/agl/aglw/aquastat/water_use/index.stm.

Forsythe, W.C., Rykiel, E.J., Stahl, R.S., Wu, H. & Schoolfield, R.M. (1995): A model comparison for daylength as a function of latitude and day of year. Ecol. Model. 80, 87–95.

Geng, S., Penning, F. W. T. & Supit, I. (1986): A simple method for generating daily rainfall data, Agric. For. Meteorol., 36, 363–376.

Hutson, S. S., Barber, N. L., Kenny, J. F., Linsey, K. S., Lumia, D. S. & Maupin, M. A. (2004): Estimated use of water in the United States in 2000. U.S. Geological Survey circular 1268, Reston, United States, available at: http://water.usgs.gov/watuse/.

Lehner, B., Döll, P., Alcamo, J., Henrichs, H. & Kaspar, F. (2006): Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. Climatic Change, 75, 273–299. DOI: 10.1007/s10584-006-6338-4.

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, 693-712.

Nash, J. E. & Sutcliffe, J. V. (1970): River flow forecasting through conceptual models, Part I – A discussion of principles. Journal of Hydrology 10, 282-290.

New, M., Hulme, M. & Jones, P. (1999): Representing Twentieth-Century Space-Time Cimate Variability. Part I: Development of a 1961-90 Mean Monthly Terrestrial Climatology in "Journal of Climate" Volume 12, March 1999.

New, M., Lister, D., Hulme, M. & Makin, I. (2002): A high-resolution data set of surface climate over global land areas. Climate Research, 21(1), 1-25.

Nicolaescu, I., Buhociu, L., Condruz, R., Suciu, G.-I., Paraschiv, D. & Boeru, M. (2006): Country report from Romania. In: Dirksen, W. and Huppert, W. (ed.). Irrigation sector reform in Central and Eastern European countries. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany, 385-462.

NOAA (1988): Data Announcement 88-MGG-02, Digital relief of the Surface of the Earth. NOAA, National Geophysical Data Center, Boulder, Colorado.

Oki, T. & Kanae, S. (2004), Virtual water trade and world water resources, Water Science & Technology, 49 (7), 203-209.

Portmann, F., Siebert, S., Bauer, C. & Döll, P. (2008): Global data set of monthly growing areas of 26 irrigated crops. Frankfurt Hydrology Paper 06, Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, available at: http://www.geo.uni-frankfurt.de/fb/fb11/ipg/ag/dl/f_publikationen/2007/FHP_06_Portmann_et_al_2008.pdf

Press, W. H., Flannery, B. P., Teukolsky, S. A. & Vetterling, W. T. (1992): Numerical recipes in C: the art of scientific computing. Cambridge University Press, 994 pp.

Priestley, C., & Taylor, R. (1972): On the assessment of surface heat flux and evaporation using large scale parameters, Mon. Weather Rev., 100, 81– 92.

Seckler, D., Amarasinghe, U., Molden, D., De Silva, R. & Barker, R. (2000): World water demand and supply 1990 to 2025: scenarios and issues. IWMI Research Report 19, IWMI, Colombo, Sri Lanka, 40 pp.

Shiklomanov, I. A. (2000): Appraisal and assessment of world water resources. Water International, 25(1), 11-32.

Shuttleworth, W. J. (1993): Evaporation, in Handbook of Hydrology, edited by D. R. Maidment, pp. 4.1–4.53, McGraw-Hill, New York.

Siebert, S., Hoogeveen, J. & Frenken, K. (2006): Irrigation in Africa, Europe and Latin America. Update of the Digital Global Map of Irrigation Areas to Version 4. Frankfurt Hydrology Paper 05, Institute of Physical Geography, Frankfurt University, Frankfurt am Main, Germany, 134 pp.

Siebert, S., Döll, P. & Hoogeveen, J. (2002): Global map of irrigated areas version 2.1. Center for Environmental Systems Research, University of Kassel, Germany, and FAO, Rome, Italy.

Solley, W. B., Pierce, R. R. & Perlman, H. A. (1998): Estimated use of water in the United States in 1995. U.S. Geological Survey circular 1200, Denver, United States, available at: http://water.usgs.gov/watuse/.

Vörösmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. (2000): Global water resources: vulnerability from climate change and population growth. Science, 289, 284–288.

Yang, H., Wang, L., Abbaspour, K.C. & Zehnder, A.J.B. (2006): Virtual water highway: water use efficiency in global food trade. Hydrology & Earth System Sciences 3, 1–26.

Annex A - Tables

TABLE A1

Irrigated area harvested (*IAH*) in ha yr^{-1}, total irrigation water requirement (IWR_{tot}) in km^3 yr^{-1}, crop water use from green water (CWU_{green}) in km^3 yr^{-1}, irrigation water requirement related to *IAH* (IWR_{IAH}) in mm yr^{-1} and percentage of crop evapotranspiration from irrigation water (IWR_{frac}) computed for irrigated land by using the Global Crop Water Model (GCWM) in the period 1998 – 2002 (only countries with irrigated area are listed).

Country	*IAH** (ha yr^{-1})	IWR_{tot} (km^3 yr^{-1})	CWU_{green} (km^3 yr^{-1})	IWR_{IAH} (mm yr^{-1})	IWR_{frac} (%)
Afghanistan	1,912,917	9.4401	2.5582	493	79
Albania	180,000	0.7415	0.6305	412	54
Algeria	570,447	4.2781	0.9566	750	82
Andorra	150	0.0003	0.0004	182	39
Angola	42,000	0.2059	0.1068	490	66
Antigua and Barbuda	130	0.0001	0.0007	67	12
Argentina	1,352,379	5.7517	5.7290	425	50
Armenia	172,806	0.5967	0.3068	345	66
Australia	2,384,292	13.6380	10.8816	572	56
Austria	41,076	0.0346	0.1502	84	19
Azerbaijan	730,129	3.8453	1.1763	527	77
Bahrain	3,113	0.0396	0.0007	1272	98
Bangladesh	6,431,077	18.6735	24.3373	290	43
Barbados	1,000	0.0017	0.0050	169	25
Belarus	115,000	0.1522	0.4952	132	24
Belgium	10,378	0.0050	0.0289	48	15
Belize	3,000	0.0044	0.0201	145	18
Benin	2,823	0.0132	0.0134	468	50
Bhutan	43,507	0.0573	0.2269	132	20
Bolivia	127,001	0.4168	0.3346	328	55
Bosnia and Herzegovina	3,000	0.0110	0.0106	368	51
Botswana	620	0.0037	0.0016	595	70
Brazil	2,820,954	8.3360	18.0386	296	32
Brunei	1,000	0.0006	0.0067	56	8
Bulgaria	50,898	0.1208	0.1265	237	49
Burkina Faso	20,233	0.1268	0.0730	627	63
Burundi	20,130	0.0690	0.0771	343	47
Cambodia	336,992	1.0450	1.7786	310	37
Cameroon	45,079	0.2055	0.1567	456	57
Canada	707,053	2.7152	2.3464	384	54
Cape Verde	2,578	0.0104	0.0113	405	48
Central African Republic	69	0.0001	0.0003	170	32
Chad	26,804	0.1404	0.1008	524	58
Chile	897,274	2.9951	2.0670	334	59
China	85,655,033	147.2152	256.7833	172	36
Colombia	645,000	0.9615	3.6763	149	21
Comoros	85	0.0003	0.0008	295	23
Congo, Dem. Rep.	7,771	0.0234	0.0522	301	31
Congo, Rep	2,000	0.0045	0.0148	223	23
Costa Rica	123,030	0.4344	0.8682	353	33
Cote D'Ivoire	41,618	0.1405	0.3253	338	30
Croatia	5,000	0.0097	0.0210	195	32
Cuba	822,225	1.6176	6.2182	197	21
Cyprus	36,210	0.2753	0.0765	760	78
Czech Republic	16,554	0.0206	0.0727	125	22
Denmark	204,071	0.0473	0.5123	23	8
Djibouti	388	0.0025	0.0005	641	84
Dominican Republic	220,000	0.9041	1.5057	411	38
Ecuador	686,000	2.7200	2.1122	397	56
Egypt	6,027,115	46.9247	0.7647	779	98

Country	IAH^* (ha yr^{-1})	IWR_{tot} (km^3 yr^{-1})	CWU_{green} (km^3 yr^{-1})	IWR_{IAH} (mm yr^{-1})	IWR_{frac} (%)
El Salvador	50,710	0.2107	0.2543	415	45
Eritrea	5,969	0.0390	0.0131	653	75
Estonia	600	0.0004	0.0023	71	16
Ethiopia	410,557	1.1919	1.4011	290	46
Fiji	3,000	0.0003	0.0145	8	2
Finland	20,000	0.0095	0.0594	48	14
France	1,708,020	3.2194	6.0108	188	35
French Guyana	6,007	0.0081	0.0325	135	20
Gabon	8,450	0.0124	0.0260	147	32
Gambia	2,149	0.0104	0.0065	482	61
Georgia	196,702	0.4917	0.6376	250	44
Germany	266,827	0.2113	0.9083	79	19
Ghana	17,138	0.0518	0.0513	302	50
Greece	1,237,967	6.9304	2.4991	560	73
Grenada	218	0.0004	0.0008	181	32
Guadeloupe	5,697	0.0043	0.0651	76	6
Guam	312	0.0000	0.0017	0	0
Guatemala	139,788	0.6541	1.2307	468	35
Guinea	20,386	0.0698	0.0917	342	43
Guinea Bissau	8,562	0.0538	0.0485	628	53
Guyana	178,029	0.3284	1.2397	184	21
Haiti	89,000	0.2322	0.5105	261	31
Honduras	100,000	0.3605	0.5626	360	39
Hungary	103,764	0.2061	0.3819	199	35
India	68,724,872	286.9738	174.9560	418	62
Indonesia	7,108,333	13.5840	43.2047	191	24
Iran	7,296,524	40.7829	10.6871	559	79
Iraq	2,439,000	20.8607	2.1195	855	91
Ireland	1,100	0.0005	0.0039	41	10
Israel	184,072	1.5371	0.1554	835	91
Italy	2,670,358	6.4612	8.7693	242	42
Jamaica	24,666	0.0546	0.2684	221	17
Japan	2,167,228	1.6519	9.0626	76	15
Jordan	100,105	0.7760	0.0754	775	91
Kazakhstan	1,804,753	8.8560	3.1984	491	73
Kenya	76,813	0.4549	0.3322	592	58
Korea, Democratic People's Republic of	1,278,000	1.1048	5.5678	86	17
Korea, Republic of	875,415	0.8358	4.0216	95	17
Kuwait	8,509	0.0730	0.0039	858	95
Kyrgyzstan	1,140,614	3.1238	2.5500	274	55
Laos	354,642	1.2797	1.4057	361	48
Latvia	833	0.0007	0.0026	81	20
Lebanon	139,292	0.9677	0.2213	695	81
Lesotho	203	0.0004	0.0003	200	62
Liberia	2,100	0.0029	0.0075	140	28
Libya	316,000	2.6761	0.2874	847	90
Lithuania	4,416	0.0031	0.0149	71	17
Luxembourg	24	0.0000	0.0000	72	26
Macedonia	42,500	0.1915	0.1254	451	60
Madagascar	1,105,685	2.8126	4.3617	254	39
Malawi	56,515	0.3440	0.3542	609	49
Malaysia	501,606	0.6150	2.8419	123	18
Mali	180,317	1.2675	0.3980	703	76
Malta	3,540	0.0144	0.0043	407	77
Martinique	6,730	0.0128	0.0776	190	14
Mauritania	23,084	0.1996	0.0437	864	82
Mauritius	20,919	0.0789	0.2031	377	28
Mexico	5,958,094	26.8002	24.2360	450	53

Country	IAH^* (ha yr^{-1})	IWR_{tot} (km^3 yr^{-1})	CWU_{green} (km^3 yr^{-1})	IWR_{IAH} (mm yr^{-1})	IWR_{frac} (%)
Moldova Republic of	256,377	0.7089	0.6355	277	53
Mongolia	57,300	0.2965	0.0866	518	77
Montenegro	2,109	0.0048	0.0084	229	36
Morocco	1,468,600	8.9690	2.2344	611	80
Mozambique	40,063	0.1681	0.2393	419	41
Myanmar	2,263,062	5.9249	6.5030	262	48
Namibia	8,806	0.0672	0.0187	764	78
Nepal	1,257,984	4.2003	3.9909	334	51
Netherlands	153,650	0.1234	0.7749	80	14
New Zealand	383,236	0.6842	2.1011	179	25
Nicaragua	75,222	0.3338	0.4115	444	45
Niger	96,125	0.6165	0.2079	641	75
Nigeria	164,000	0.8873	0.6452	541	58
Northern Mariana Islands	60	0.0000	0.0004	0	0
Norway	36,200	0.0151	0.1416	42	10
Oman	72,461	1.0588	0.0639	1461	94
Pakistan	19,344,802	117.0439	19.2518	605	86
Palestine (Gaza Strip and West Bank)	29,197	0.2018	0.0171	691	92
Panama	30,811	0.0598	0.2911	194	17
Paraguay	54,000	0.0894	0.4984	166	15
Peru	1,108,999	5.0700	1.4412	457	78
Philippines	2,067,000	3.7971	10.3969	184	27
Poland	83,292	0.1038	0.3219	125	24
Portugal	638,947	3.2463	1.8630	508	64
Puerto Rico	17,465	0.0432	0.1926	248	18
Qatar	9,544	0.0839	0.0023	879	97
Reunion	7,584	0.0077	0.0599	101	11
Romania	422,724	0.9003	1.2530	213	42
Russian Federation	3,772,922	11.6267	13.3821	308	46
Rwanda	5,500	0.0118	0.0167	214	41
Saint Kitts and Nevis	18	0.0000	0.0001	59	14
Saint Lucia	297	0.0005	0.0030	179	15
Sao Tome and Principe	9,700	0.0186	0.1048	191	15
Saudi Arabia	1,280,725	12.3795	0.7229	967	94
Senegal	83,904	0.6041	0.2002	720	75
Serbia (including Kosovo)	60,071	0.1580	0.2441	263	39
Seychelles	224	0.0005	0.0008	217	39
Sierra Leone	30,000	0.1167	0.1091	389	52
Slovakia	104,560	0.1912	0.3658	183	34
Slovenia	10,324	0.0056	0.0476	55	11
Somalia	206,000	0.9809	0.6510	476	60
South Africa	1,664,300	8.8129	6.4502	530	58
Spain	3,423,510	18.6311	9.1600	544	67
Sri Lanka	731,700	2.2227	2.9985	304	43
Sudan	1,208,110	10.0950	2.8930	836	78
Suriname	51,180	0.0941	0.3144	184	23
Swaziland	45,482	0.2656	0.3088	584	46
Sweden	53,440	0.0479	0.2028	90	19
Switzerland	14,500	0.0009	0.0414	6	2
Syria	1,507,867	9.4585	2.1962	627	81
Taiwan, Province of China	588,798	0.6837	2.6261	116	21
Tajikistan	637,213	3.2782	1.0146	514	76
Tanzania	227,000	0.9838	0.8119	433	55
Thailand	6,187,300	19.0901	30.8103	309	38
Timor Leste (East Timor)	7,000	0.0123	0.0443	176	22
Togo	2,557	0.0120	0.0146	469	45
Trinidad and Tobago	3,600	0.0090	0.0363	250	20
Tunisia	367,000	2.5949	0.7089	707	79

Country	IAH^* (ha yr^{-1})	IWR_{tot} (km^3 yr^{-1})	CWU_{green} (km^3 yr^{-1})	IWR_{IAH} (mm yr^{-1})	IWR_{frac} (%)
Turkey	3,476,000	14.6287	6.6360	421	69
Turkmenistan	1,402,828	10.6086	1.3332	756	89
Uganda	2,330	0.0080	0.0082	342	49
Ukraine	1,005,120	3.4935	3.5993	348	49
United Arab Emirates	204,951	3.3127	0.0981	1616	97
United Kingdom	183,461	0.2141	0.6482	117	25
United States of America	20,548,479	139.1132	79.1446	677	64
Uruguay	216,979	0.5998	0.9534	276	39
US Virgin Islands	185	0.0004	0.0022	199	15
Uzbekistan	3,819,097	24.1327	5.5365	632	81
Venezuela	491,000	1.9956	3.3560	406	37
Vietnam	5,228,400	7.4078	24.7193	142	23
Yemen	399,668	2.9333	0.5058	734	85
Zambia	55,387	0.3661	0.2094	661	64
Zimbabwe	202,816	0.9303	0.6646	459	58
World	312,415,845	1180.5094	918.9184	378	56

Annex B - Figures

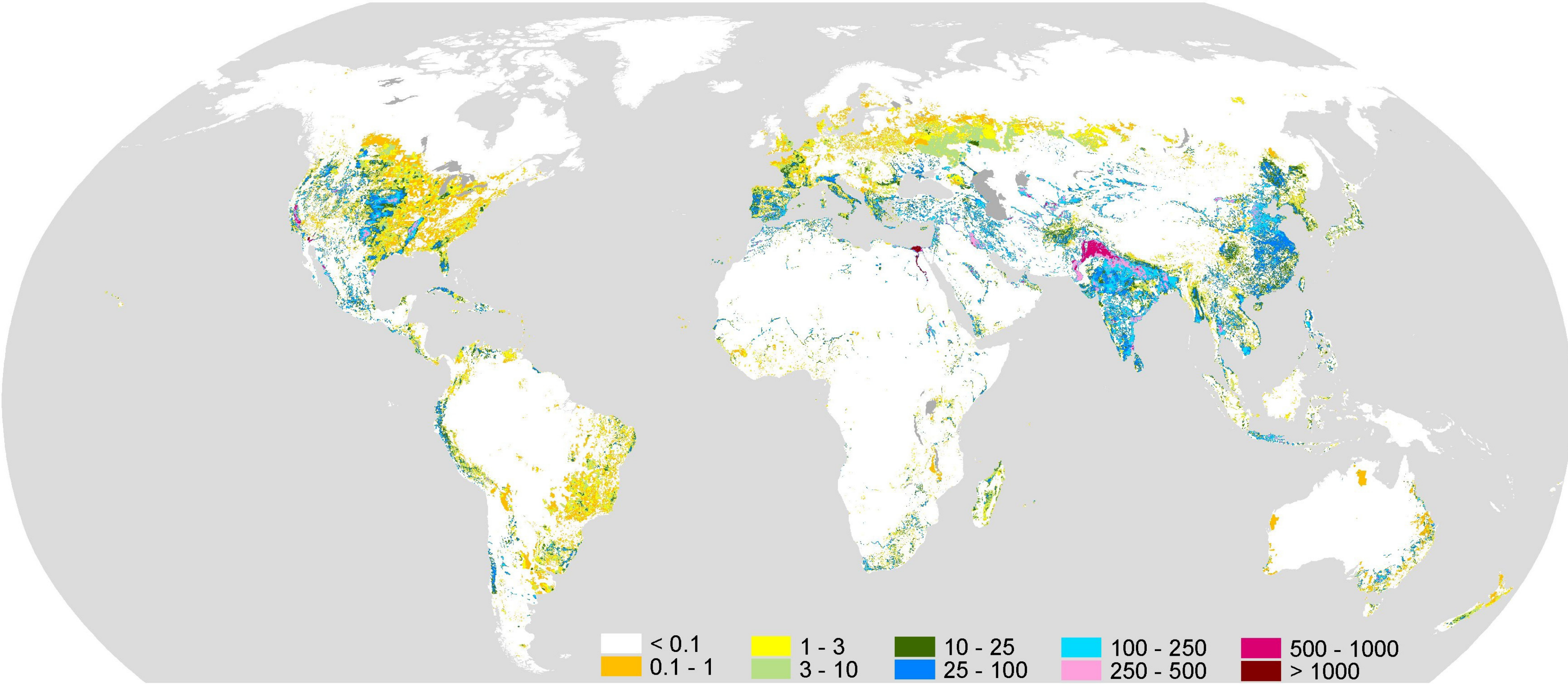


FIGURE B1

Mean blue water requirement during period 1998 – 2002 averaged over entire 5 arc minute cell area in mm yr^{-1}.

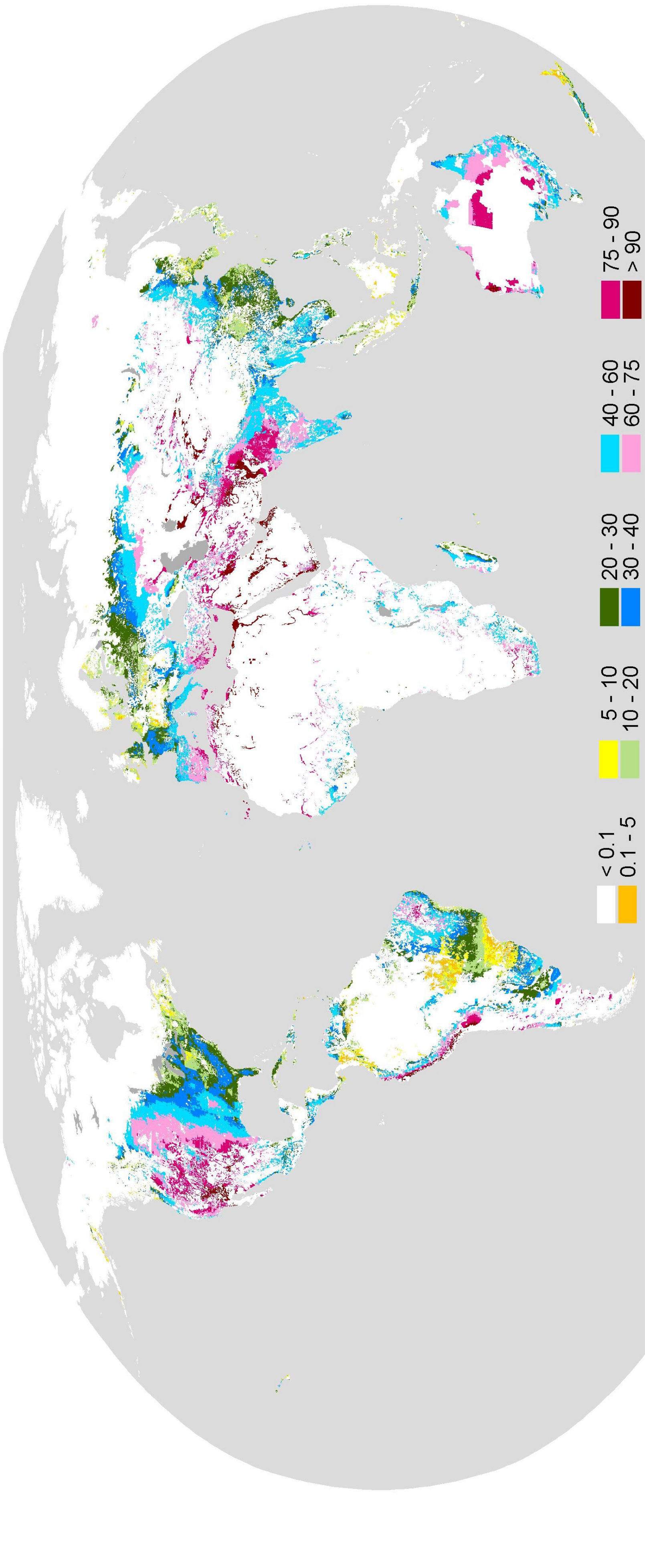


FIGURE B2
Percentage of total crop evapotranspiration on irrigated cropland coming from blue (irrigation) water average over 5 minute cells during period 1998 – 2002.

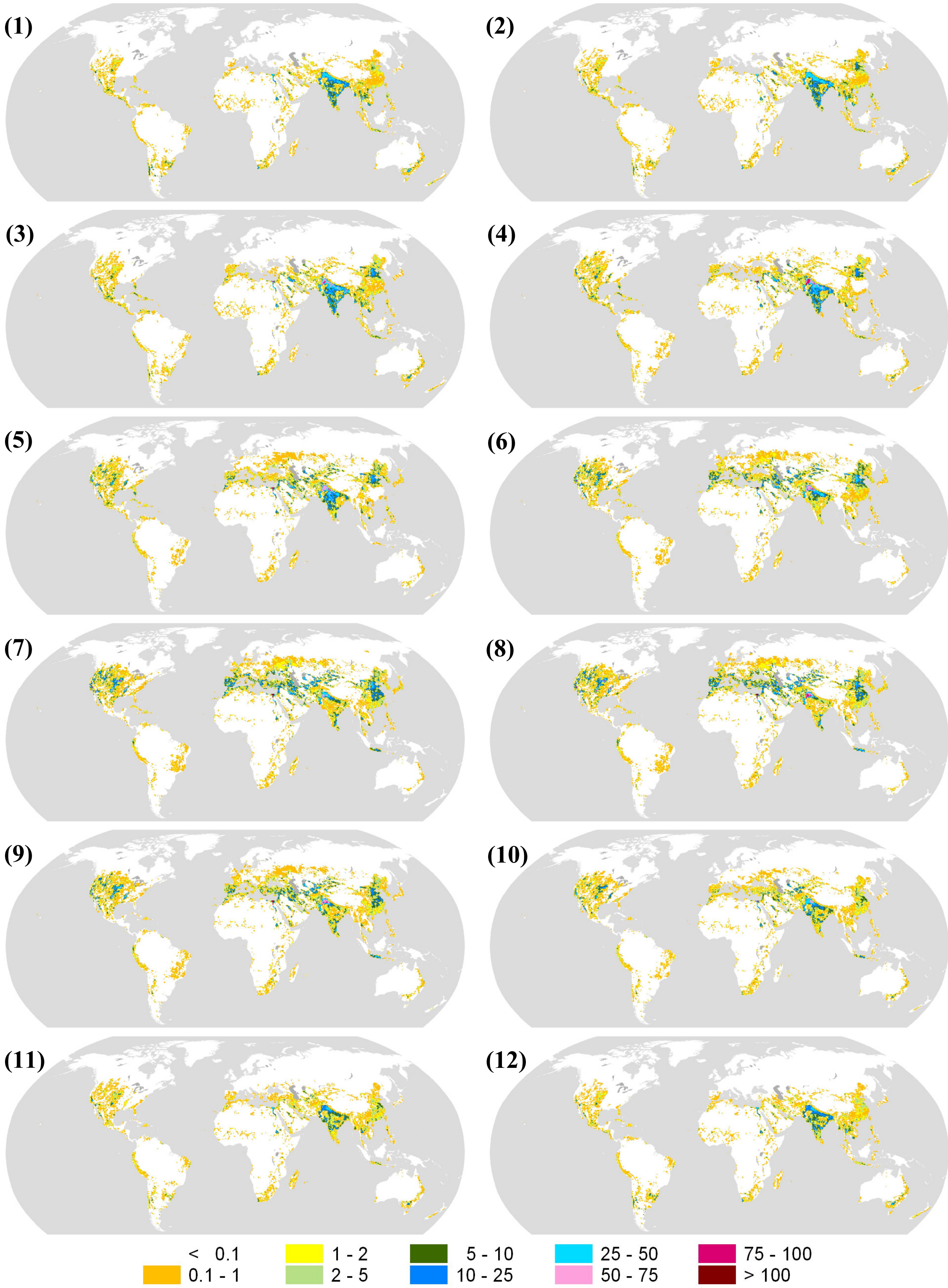


FIGURE B3

Mean monthly total blue water requirement during period 1998 – 2002 averaged over entire 30 arc minute cells in mm month^{-1} for January (1), February (2), March (3), April (4), May (5), June (6), July (7), August (8), September (9), October (10), November (11) and December (12).

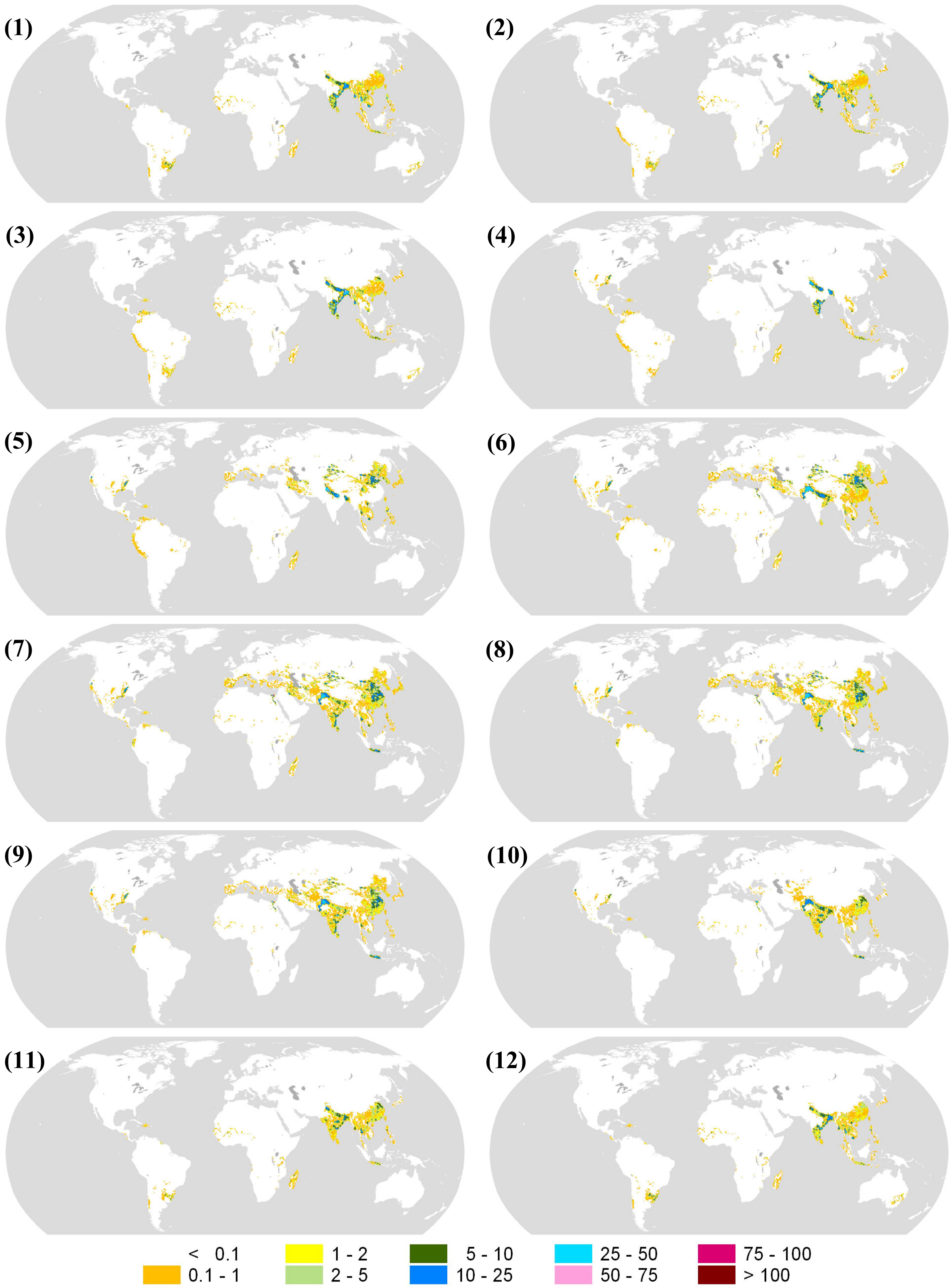


FIGURE B4

Mean monthly total blue water requirement for rice during period 1998 – 2002 averaged over entire 30 arc minute cells in mm month^{-1} for January (1), February (2), March (3), April (4), May (5), June (6), July (7), August (8), September (9), October (10), November (11) and December (12).

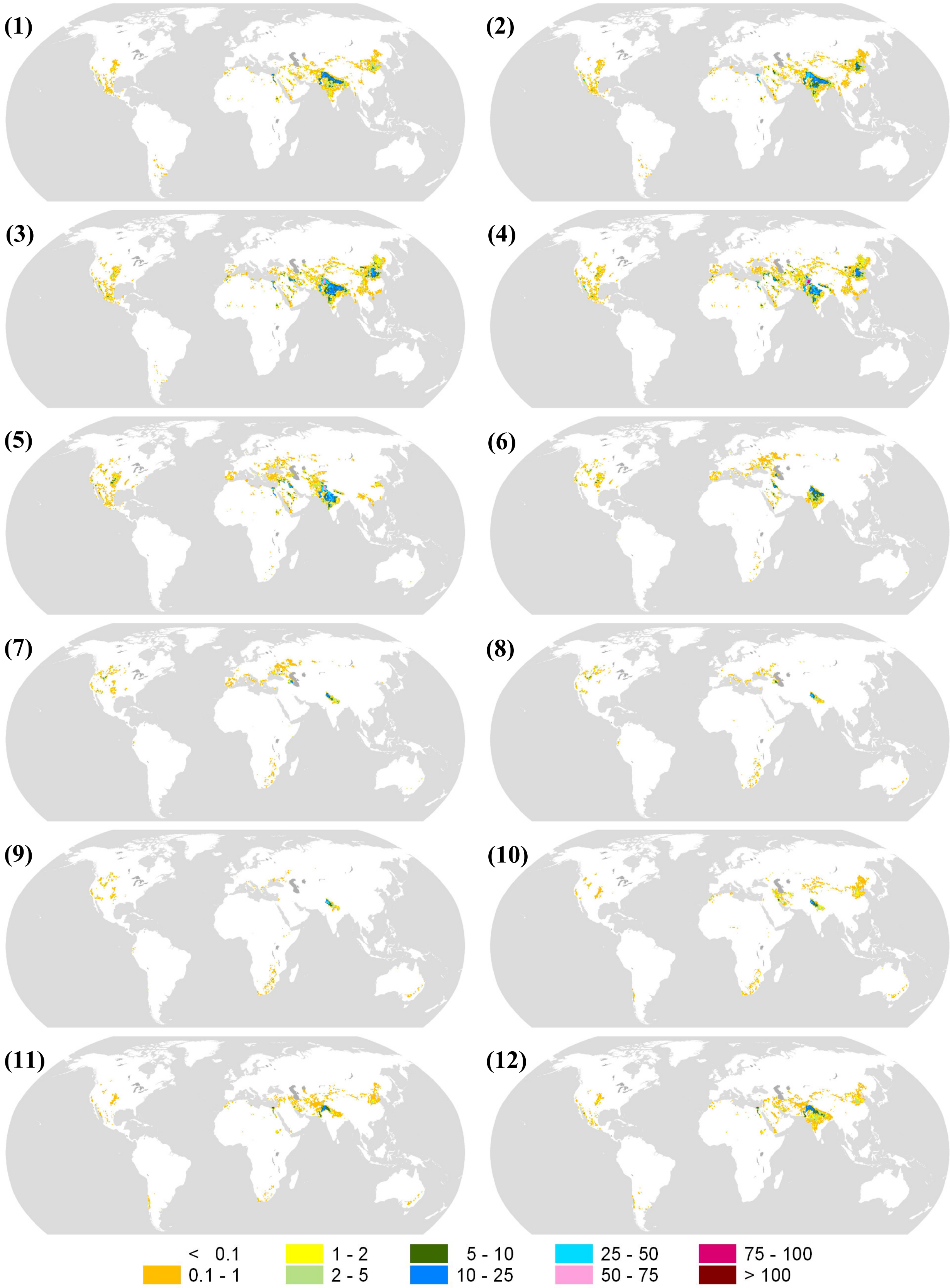


FIGURE B5

Mean monthly total blue water requirement for wheat during period 1998 – 2002 averaged over entire 30 arc minute cells in mm month^{-1} for January (1), February (2), March (3), April (4), May (5), June (6), July (7), August (8), September (9), October (10), November (11) and December (12).