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Global modeling of irrigation water requirements

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[1] Currently, almost 90% of the global water consumption is for irrigation purposes, and more than 40% of the crops are produced under irrigated conditions. In order to assess the future water and food situation, it is therefore necessary to model irrigation water requirements. We present a global model of irrigation requirements, which is based on a new raster map of irrigated areas. With a spatial resolution of 0.5°, the model simulates the cropping patterns, the growing seasons, and the net and gross irrigation requirements, distinguishing two crops, rice and nonrice. Using long time series of monthly climatic variables, the irrigation requirements under present-day climate conditions are computed, and the impact of climate variability is analyzed. The correspondence between model results and independent estimates of irrigation water use is judged to be good enough for applying the model in global and continental studies. *INDEX TERMS:* 1842 Hydrology: Irrigation; 1818 Hydrology: Evapotranspiration; 1836 Hydrology: Hydrologic budget (1655)

1. Introduction

[2] According to United Nations Environmental Programme's (UNEP) Global Environmental Outlook 2000, freshwater scarcity is viewed by both scientists and politicians as the second most important environmental issue of the 21st century. "The world water cycle seems unlikely to be able to cope with demands in the coming decades" [*United Nations Environmental Programme*, 1999]. Only the topic of climate change is mentioned more often than water scarcity. Today, about 67% of the global water withdrawal and 87% of the consumptive water use (withdrawal minus return flow) is for irrigation purposes [*Shiklomanov*, 1997]. Irrigated agricultural land comprises less than a fifth of all cropped area but produces 40–45% of the world's food. It is generally expected that irrigated agriculture will have to be considerably extended in the future in order to feed growing populations (an additional 1.5–2 billion people by 2025, according to United Nations population projections). However, it is not yet known whether there will be enough water available for the necessary extension. As it is very likely that water demands of the domestic and industrial sectors will increase in the future, even regions that do not have water scarcity problems today will be restricted in their agricultural development and thus possibly their food security by a lack of water availability.

[3] For an assessment of the future water and food situation, it is therefore necessary to model the water requirement of irrigated agriculture. Here, "water requirement" means the amount of water that must be applied to the crop by irrigation to achieve optimal crop growth. Modeling of today's irrigation water requirements as a function of irrigated area, climate, and crops provides the basis for estimating the future impact of climate change as well as demographic, socioeconomic, and technological changes. It does not only help to find sustainable development paths for the future, but, for many regions, it also improves our knowledge about the current water use situation. Existing information on current and historic water use is generally poor, and modeling brings together various types of information that are not combined otherwise.

[4] In almost no country is there a good measurement and registration system for water use in general and irrigation water use in particular. For assessments at the continental and global scale the smallest spatial units for which data on water withdrawals are available are countries (compilation by *World Resources Institute-WRI* [1998]). However, drainage basins and not countries are considered to be the appropriate spatial unit for water resources issues, and thus the country-level data available need to be translated to smaller spatial units. Besides, the country data of total annual water withdrawals are not provided for the same year but refer to different years from 1970 to 1995. For most countries the partitioning into the sectoral withdrawals for households, industry, and agriculture represents an estimate for the year 1987 and not for the year for which the total withdrawal is provided. Finally, there are only data for water withdrawal but not for consumptive water use.

[5] In order to estimate the impact of climatic, demographic, socioeconomic, and technological change on the problem of water scarcity, we are developing a global model of water resources and water use, named WaterGAP (Water-Global Assessment and Prognosis). WaterGAP has a spatial resolution of 0.5° longitude by 0.5° latitude and is designed to provide information on the scale of river basins. As we want to identify water scarcity by comparing water demand to water availability, we do not model actual irrigation water use but irrigation water requirements, i.e., the irrigation water use that would lead to optimal crop growth. (Actual irrigation water use may be lower than the requirement because of, for example, water scarcity). In the first versions of WaterGAP [*Alcamo et al.*, 1997; *Döll et al.*, 1999], the irrigation requirements were modeled in a very rough manner, mainly because no information on the location of irrigated areas within countries was available, such that the current spatial distribution of irrigated areas had to be modeled, too. To our knowledge, it was the first attempt to globally model irrigation water use with a spatial resolution below the country scale. *Seckler et al.* [1997], for example, presented a global assessment in which irrigation requirements are merely modeled on the country level. *Food and Agriculture Organization of the United Nations (FAO)* [1997], on the other hand, restricted its modeling efforts to Africa but subdivided the continent into 137 spatial units that were composed by overlaying the boundaries of 24 large drainage basins and 53 countries.

[6] This paper presents our improved global model of irrigation water requirements and its application for present-day conditions,

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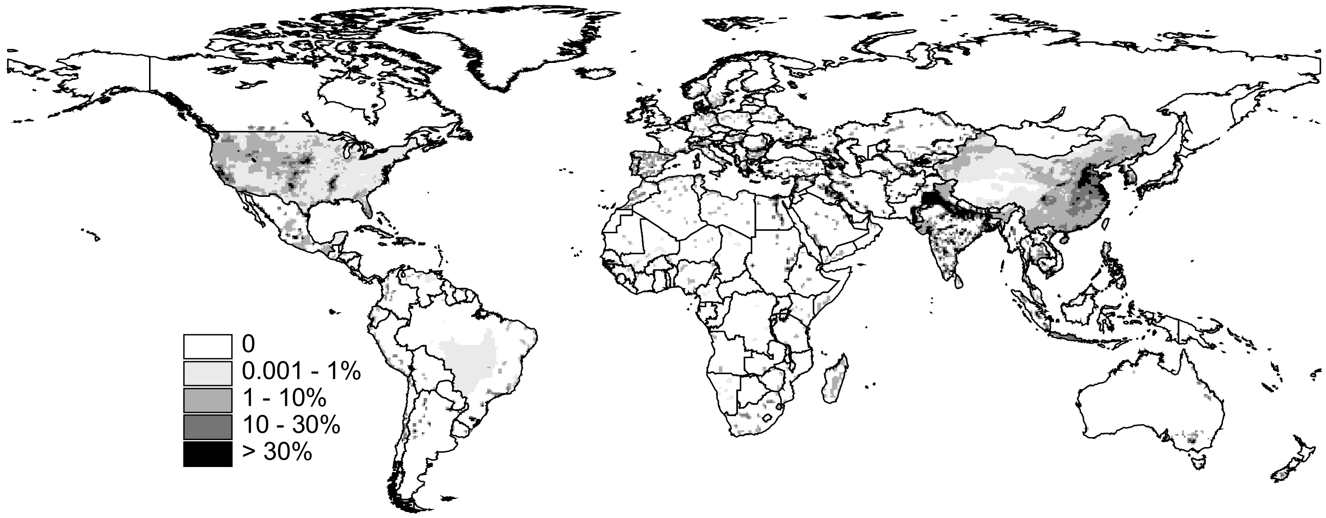

Figure 1. Digital global map of irrigated areas showing the fraction of each 0.5° by 0.5° cell area that was equipped for irrigation around 1995 (in percent).

which forms part of version 2 of WaterGAP. It is based on a global map of irrigated areas that shows the fraction of each 0.5° by 0.5° cell that was equipped for irrigation around 1995 (described in section 2). The irrigation requirement per unit irrigated area is computed as a function of climate, cropping intensity, and crop type (section 3). As there is not sufficient information available on what crops are grown under irrigated conditions where and when, the cropping patterns and the growing seasons are also simulated by the model, based on soil suitability and climate. Furthermore, we distinguish only two crop types, rice and nonrice. The model results presented in section 4 include not only the irrigation requirements under average climatic conditions but also in typical dry years; for an assessment of water scarcity, it is important to know the water situation in dry years, when the higher than normal irrigation requirement can possibly not be fulfilled by the lower than normal water availability. In section 5 the reliability of the model results is discussed by comparing them with independent data, and, in section 6, conclusions regarding the applicability of the model are drawn.

2. Digital Global Map of Irrigated Areas

[7] According to FAO, there is irrigation in 174 out of 225 countries worldwide. FAO provides data on the total irrigated area within each country but does not include information on the location of the irrigated areas within the country. Such information is given by large-scale irrigation maps that show, for one or more countries, the outlines of areas in which irrigation is wide-spread. Adding up all these areas within a country, however, would lead to a gross overestimation of the irrigated area because only a fraction of these relatively large "irrigated areas" is actually equipped for irrigation. For a map of irrigated areas that is appropriate for quantitative assessments and modeling, information on the (approximate) location of irrigated areas has to be linked with information on the total irrigated area within a spatial unit, for example, a country or a drainage basin.

[8] As no such map existed, we generated a digital global map by combining information from large-scale maps, FAO data on total irrigated area per country in 1995, and, where available, national data on total irrigated area per county, drainage basin, or federal state [*Döll and Siebert*, 2000]. The global map of irrigated areas (Figure 1) is a raster map with a resolution of 0.5° by 0.5°, which is also the resolution of the WaterGAP model (~67,000 cells). For the whole land area of the globe (except Antarctica) the data set provides the irrigation density in 1995, i.e., the percentage of each 0.5° by 0.5° cell area that was equipped for controlled irrigation in 1995. Flood recession cropping areas and cultivated wetlands (as specified in FAO's AQUASTAT database [*FAO*, 1995a]) are not included in the map. The area equipped for irrigation that is indicated on the map is 2,549,093 km^2. Of the total area, 68% is in Asia, 16% in America, 10% in Europe, 5% in Africa, and 1% in Australia. The area actually irrigated in 1995 was smaller, but is mostly unknown. In the context of the map, "area equipped for irrigation" is abbreviated to "irrigated area."

[9] In order to generate the digital global map of irrigated areas, for most countries the maps by *Achtnich* [1980] and values of the total irrigated area within the country from the FAO databases AQUASTAT or FAOSTAT (http://www.fao.org) were used. For the countries with the globally largest irrigated areas, more detailed information was obtained. India, China, and the Untied States are the three most important irrigating countries, totaling 47% of the global irrigated area. For India, a national map of irrigated areas and data of the total irrigated area in each federal state could be obtained [*Central Board of Irrigation and Power*, 1994; A.R.G. Rao, Central Board of Irrigation and Power, New Delhi, personal communication, 1998], while for China and the United States, values of the irrigated area in each county were available [*Skinner*, 1996; *Solley et al.*, 1998]. Out of the ten countries with the largest irrigated areas (66% of the global irrigated area), information on irrigated area within subnational units (counties, drainage basins, or federal states) was accessible for six. For five additional countries, information on the irrigated area in each federal state or drainage basin could be taken into account. Thus 44% of the global irrigated area was assigned based on an irrigation map plus the value of the irrigated area of the specific country, while 27% was based on county data and 25% on an irrigation map plus the value of the irrigated area in the federal states of the respective country.

[10] Unfortunately, the information provided by the global map of irrigated areas is rather uncertain. The uncertainty is due to the fact that errors in the map generation process is lower than that resulting from the (low) quality of the used input data, i.e., the total area equipped for irrigation per country (or subnational unit) and

the maps with outlines of irrigated areas. In spite of the uncertainties, the generated global map of irrigated areas is, in our opinion, appropriate for use in global and continental assessments. The data set together with an extensive documentation [*Döll and Siebert*, 1999], which describes the data sources and the map generation process and also discusses the map quality, is available from the authors.

3. Methodology for Computing Irrigation Water Requirements

[11] Water is often a limiting factor for crop growth, especially in arid and semi-arid regions, but even in some in humid areas. In order to achieve optimal crop productivity, a certain amount of water must be applied to the soil such that evapotranspiration may occur at the potential rate. Only part of the applied water is actually ‘‘used’’ by the plant and evapotranspirates; this amount, the difference between the potential evapotranspiration and the evapotranspiration that would occur without irrigation, is the net irrigation requirement. The other part of the added water serves to leach salts from the field soils, leaks or evaporates unproductively from the irrigation canals, or runs off; this amount depends on irrigation technology and management. The ratio of the net irrigation water requirement and the total amount of water that needs to be withdrawn from the source, the gross irrigation requirement, is called ‘‘irrigation water use efficiency.’’ Under conditions of restricted water availability, farmers may choose to irrigate at a lower than optimal rate. Then the actual water withdrawal is less than the gross irrigation requirement, and, equally, the actual consumptive water use for irrigation is less than the net irrigation requirement. Our model is restricted to computing the net and gross irrigation requirements.

[12] The potential evapotranspiration is crop-specific and depends on the growing stage of the crop. Therefore it is necessary to determine which crops are irrigated in each cell. This, however, is very difficult; for most countries, there are not even countrywide values for the crop-specific irrigated areas. An exception is rice, for which the International Rice Research Institute publishes data on areas under controlled irrigation in the most important rice producing countries [*International Rice Research Institute* (*IRRI*), 1988]. This is why the presented global irrigated model distinguishes only between rice and nonrice crops.

[13] The computation of the net and gross irrigation requirements is done in three steps. First, the cropping pattern is modeled, i.e., the irrigated rice and nonrice cropping areas of each cell during the first and the second growing season (that is if a second growing season exists) are calculated. Then, the optimal growing seasons are determined for each cell. Finally, the net irrigation requirement of the rice and nonrice crop is computed for each day of the growing season, and the gross irrigation requirement is calculated by taking into account the irrigation water use efficiency. Each modeling step requires information on the cell-specific climatic conditions. For the modeling of cropping patterns and growing seasons, the long-term average climate is taken into account, as farmers do not base their planting decisions on the unknown weather during the growing season that is yet to begin. The irrigation requirements, however, are calculated for specific years by using time series of climatic data.

3.1. Climate Input

[14] The global irrigation model requires information on precipitation, temperature, and potential evapotranspiration for each grid cell. Long time series of these climate data are necessary in order to analyze the impact of climate variability on irrigation requirements. *New et al.* [2000] collected observed monthly values of precipitation, temperature, sunshine, and number of wet days and interpolated them on a grid of 0.5° × 0.5°. While for sunshine, only the long-term average values of the period 1961–1990 are provided, the complete time series between 1901 and 1995 is available for precipitation, temperature, and number of wet days. We corrected the precipitation values for measurement errors using the monthly 0.5° × 0.5° correction factors of *Legates and Willmott* [1990], who developed a model to estimate and remove the bias in precipitation gauge measurements caused by wind, wetting, and evaporation losses.

[15] The WaterGAP model calculations are performed with a temporal resolution of 1 day. Daily values of temperature and sunshine are calculated from the monthly values using cubic splines. Synthetic daily precipitation values are generated from the corrected monthly values by using the information on the number of wet days per month, such that there are days with and without precipitation. Following *Geng et al.* [1986], the sequence of wet and dry days in each month is simulated; then, the total monthly precipitation is distributed equally over all wet days of the month. In colder climates, precipitation may fall as snow that is available to the crop after melting. In the presented model, snowmelt is simulated using a simple degree-day approach, in which the volume of meltwater only depends on temperature.

[16] Daily potential evapotranspiration E_{pot} is computed according to *Priestley and Taylor* [1972] as a function of net radiation and temperature. Net radiation is calculated following *Shuttleworth* [1993] on the basis of the day of the year, latitude, sunshine hours, and short-wave albedo. The albedo of irrigated land is assumed to be 0.23. *Jensen et al.* [1990] tested a large number of evapotranspiration equations against measured evapotranspiration from well-watered lysimeters. For the five lysimeters in humid regions, the Priestley-Taylor equation with an α-coefficient of 1.26 gave very good agreement, while for the six lysimeters in semi-arid and arid areas, a mean α of 1.74 gave a better fit. This was explained by heat advection to the well-watered (irrigated) lysimeters. We follow the recommendation of *Shuttleworth* [1993] to set $\alpha = 1.26$ for areas with relative humidity of 60% or more and $\alpha = 1.74$ for other areas. Shuttleworth states that the thus computed potential evapotranspiration is acceptable to an accuracy of 15% for estimating the evapotranspiration of the reference crop (short grass). Therefore it is appropriate to estimate crop-specific potential evapotranspiration by multiplying E_{pot} with a crop coefficient (e.g., as given by *Smith* [1992]; compare section 3.4).

3.2. Cropping Pattern

[17] The cropping pattern for each cell with irrigated land describes (1) whether only rice, only nonrice or both are irrigated there and (2) whether, within one year, there are one or two growing seasons for rice and nonrice. We assume that the growing period for both rice and nonrice is 150 days. The following data are used to model the cropping pattern: total irrigated area, long-term average temperature and soil suitability for paddy rice in each cell, harvested area of irrigated rice in each country, and cropping intensity in each of 19 world regions (Table 1).

[18] *FAO* [1995b] provides information on the areal fraction of each cell that is not suitable for growing paddy rice. FAOSTAT lists harvested rice area per country for the year 1995 but does not distinguish between rice grown under controlled irrigation and

Table 1. Estimated Cropping Intensities for Irrigated Agriculture and Irrigation Water Use Efficiencies in the World Regions

World Region	Cropping Intensity	Irrigation Efficiency[a]
Canada	1.0	0.7
United States	1.0	0.6
Central America	1.0	0.45
South America	1.0	0.45
Northern Africa	1.5	0.7
Western Africa	1.0	0.45
Eastern Africa	1.0	0.55
Southern Africa	1.0	0.55
OECD Europe North[b]	1.0	0.5
OECD Europe South[c]	1.0	0.6
Eastern Europe	1.0	0.5
Baltic States, Belarus	0.8	0.5
Rest of former USSR	0.8	0.6
Middle East	1.0	0.6
South Asia	1.3	0.35
East Asia	1.5	0.35
South East Asia	1.2	0.4
Oceania	1.5	0.7
Japan	1.5	0.35

[a] Irrigation water use efficiency for rice is assumed to be 0.1 less.
[b] OECD is Organization for Economic Cooperative Development; area includes Austria, Belgium, Denmark, Finland, Germany, Netherlands, Norway, Sweden, Switzerland, and United Kingdom.
[c] Area includes France, Greece, Italy, Malta, Portugal, and Spain.

other types of rice production. Only for 41 important rice growing countries (out of the 113 countries with rice production), data on irrigated rice area as a fraction of the total rice area is provided, but only for years before 1988 [*IRRI*, 1988]; the average value of the period 1985–1987 is used in the model. For the other countries a diverse range of literature helped to estimate the harvested area of irrigated rice. For the European and North African countries, it is assumed that the total harvested rice area was irrigated. The harvested irrigated area is different from the irrigated area in that it already takes into account the cropping intensity: If, for example, irrigated rice is grown during two growing seasons, the harvested irrigated area is twice the irrigated area.

[19] With respect to cropping intensities, very little information is available, and we only distinguish 19 world regions, which are assumed to be homogeneous with respect to cropping intensity and irrigation water use efficiency (Table 1). In general, "cropping intensity" refers to the average number of crops that are consecutively grown within a year. If, for example, on one half of the irrigated area of a region, crops were grown only once a year, and on the other half, two crops were grown, one after the other, the average cropping intensity would be 1.5. As we assume the length of the growing season to be 150 days, both for rice and nonrice, the cropping intensity as listed in Table 1 refers to the average number of growing periods of 150 days duration each. With our definition of the growing period length, the maximum cropping intensity in each cell is 2 (300 growing days per year), while it is known that in some parts of Asia, up to three or four crops are consecutively grown within a year, each having a growing period of much less than 150 days. A cropping intensity of less than 1 means that not the total area equipped for irrigation is actually irrigated. The estimates for cropping intensity of irrigated agriculture in Table 1 are derived from *FAO* [1997] for Africa, from information by A.R.G. Rao (Central Board of Irrigation and Power, India, personal communication, 1998) for India (this value is used for South Asia), from *Alexandratos* [1995] for the other developing countries, and from O. Klepper (National Institute of Public Health and the Environment (RIVM), Bilthoven, Netherlands, unpublished report, 1996) for the rest of the world. A comparison between the estimates of *Alexandratos* [1995], who provides a value of 0.75 for Sub-Saharan Africa and *FAO* [1997] estimates for various regions in Africa shows that expert guesses of cropping intensity for irrigated areas can differ considerably; according to the FAO study, there are only two small regions with a cropping intensity of less than 1.

[20] The first step in computing the cropping pattern is to determine the potential harvested areas of irrigated rice, i.e., the areas suitable for rice of each cell in each of the two potential growing seasons and their degree of suitability. The part of the total irrigated area of a cell that is suitable for rice production because of its soil is determined, and then all possible rice growing seasons (150 consecutive days with temperatures of 12°C or higher) are identified and ranked according to a temperature criterion [*Doorenbos and Kassam*, 1979]. In the second step the harvested area of irrigated rice of each country is distributed to the most highly ranked cell/growing season combination. Even in world regions with an overall cropping intensity of 1 or less, the cropping intensity of rice can be larger than 1. In the third step, nonrice is assigned to all the irrigated areas/growing seasons where rice is not grown such that the total harvested irrigated area of the world region is the product of the cropping intensity and the irrigated area. It is assumed that in each cell with areas that are equipped for irrigation, irrigation takes place at least in the first growing period. If the regional cropping intensity is greater than one, it is necessary to do a cell ranking for nonrice similar to that for rice. After these three steps, the cropping pattern of a cell is defined. Seventeen different cropping patterns are possible, from simple ones (e.g., only nonrice during one growing season on the total irrigated area in the cell) to complex ones (nonrice in the second growing season after rice on one part of the total irrigated area cell, and nonrice after nonrice in the other part of the cell).

3.3. Growing Season

[21] Once the cropping pattern of a cell is defined, the start date of each growing season is computed for each crop and growing season. Each 150-day period within a year is ranked according to the temperature and precipitation criteria given in Table 2 for rice and nonrice. Besides, temperature must be above 5°C for nonrice and above 12°C for rice on each growing day. The temperature criterion, which follows *Doorenbos and Kassam* [1979], takes account of optimal growing conditions, while the precipitation criterion mirrors the fact that farmers prefer to start even cropping under irrigation during the wet season, while harvesting is best

Table 2. Criteria for the Optimal Starting Date for Growing Irrigated Rice and Nonrice

Growing Day	Temperature Criterion	Precipitation Criterion
	Rice	
1–30	…	$P > 0$
31–50	T [18–30°C]	$P > 0$
51–110	T [22–30°C]	$P > 0$
111–150	T [22–30°C]	$P = 0$
	Nonrice	
1–20	…	$\mathrm{avg}(P) > 0.5\mathrm{avg}(E_{\mathrm{pot}})$[a]
21–50	T [15–30°C]	$\mathrm{avg}(P) > 0.5\mathrm{avg}(E_{\mathrm{pot}})$[a]
51–110	T [15–30°C]	…
111–150	…	…

[a] Here avg( ) is a 10-day average.

done if it does not rain. If a day fulfils one of the two criteria, 1 ranking point is given. The growing season is then defined to be the most highly ranked 150-day period; in case of two consecutive growing periods the combination with the highest total number of ranking points is chosen.

3.4. Net Irrigation Requirement

[22] Following the CROPWAT approach of *Smith* [1992], the net irrigation requirement per unit irrigated area during the growing season is computed as the difference between the crop-specific potential evapotranspiration and the effective precipitation as

$$\begin{aligned} I_{\mathrm{net}} &= E_{\mathrm{pot\_c}} - P_{\mathrm{eff}} = k_c E_{\mathrm{pot}} - P_{\mathrm{eff}} && \text{if } E_{\mathrm{pot\_c}} > P_{\mathrm{eff}} \\ I_{\mathrm{net}} &= 0 && \text{if } E_{\mathrm{pot\_c}} \le P_{\mathrm{eff}}, \end{aligned} \qquad (1)$$

where

I_{net} net irrigation requirement per unit area [mm/d]

$E_{\mathrm{pot\_}c}$ crop-specific potential evapotranspiration [mm/d]

P_{eff} effective precipitation [mm/d]

E_{pot} potential evapotranspiration [mm/d]

k_c crop coefficient [dimensionless].

[23] P_{eff} is the fraction of the total precipitation P as rainfall and snowmelt that is available to the crop and does not run off. Without detailed site-specific information, P_{eff} is very difficult to determine. We use a simple approximation by following the U.S. Department of Agriculture Soil Conservation Method, as cited by *Smith* [1992, p. 21], with

$$\begin{aligned} P_{\mathrm{eff}} &= P(4.17 - 0.2P)/4.17 && \text{for } P < 8.3\,\mathrm{mm/d} \\ P_{\mathrm{eff}} &= 4.17 + 0.1\,P && \text{for } P \ge 8.3\,\mathrm{mm/d}. \end{aligned} \qquad (2)$$

Different from irrigation model presented in this paper, which uses daily time steps, CROPWAT uses calculation steps of 10 days and monthly climatic data, in particular, monthly precipitation values. The three calculation steps within a month only differ with respect to the crop coefficients k_c. This approach is roughly equivalent to modeling with a daily time step for which daily precipitation and evapotranspiration values are derived from interpolating monthly values. Application of (1) with daily precipitation values, i.e., with days with and without precipitation (compare section 3.1.), however, would lead to a gross overestimation of I_{net}. In this case the relatively high precipitation on the wet days in excess of the daily $E_{\mathrm{pot\_}c}$ would be lost (compare (1)), while a temporal averaging of the precipitation simulates the capacity of the soil to store the precipitation. Thus in order to take into account the storage capacity of the soil and to remain consistent with CROPWAT, the daily precipitation values are averaged over either 10 or 3 days. The period of 3 days is used only in the case of rice in Asia and leads to a higher irrigation requirement than the 10-day averaging. The shorter averaging period simulates the operation of paddy rice fields in Asia, where because of inundation and water-saturated soils, only little precipitation can be stored.

[24] Crop coefficients k_c depend on the growing stage of the crop. The selection of the crop coefficients (Figure 2) was based on the information given by *Doorenbos and Kassam* [1979] for rice and a large variety of other crops. For nonrice crops, optimal evapotranspiration is relatively low during the initial stage when plants are still small, and shortly before harvest when crop growth has slowed down. The very low k_c value for rice during the first 30 days mirrors the fact that in the nursery stage, only approximately 10% of the area is planted. The daily net irrigation requirement of a cell is the sum of the net requirements for rice and nonrice, while the annual requirement includes all growing seasons.

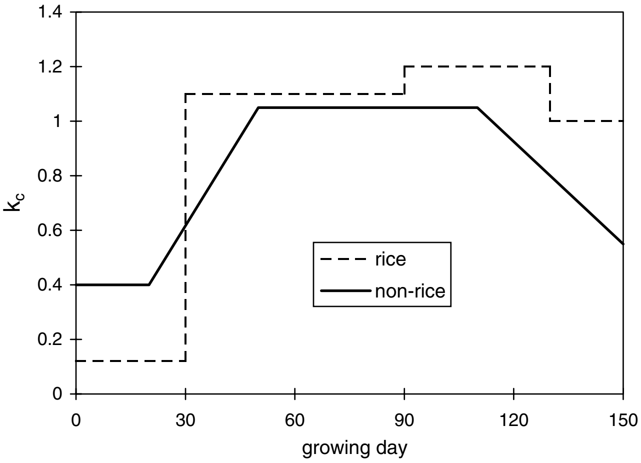

Figure 2. Crop coefficients for rice and nonrice.

[25] I_{net} is computed using time series of temperature and precipitation. It is thus possible to estimate the impact of climate variability on irrigation requirements. The long-term average I_{net} of the period 1961–1990 is calculated by averaging the I_{net} values of these 30 years. This averaging procedure leads to a more realistic estimate of the long-term average irrigation requirement than a calculation based on average climatic conditions. In the latter case the irrigation requirement may be underestimated because it is not linear with respect to precipitation and potential evapotranspiration (compare (1)). On the global average the underestimation amounts to only 2.4%, but it can be substantial in areas with a low net irrigation requirement. In Japan, for example, the error is 50%.

3.5. Gross Irrigation Requirement

[26] Consistent with the general definition of withdrawal water use (also in the domestic and industrial sectors), we compute the gross irrigation requirement by dividing the net irrigation requirement by the so-called "project efficiency of irrigation water use." This term refers to the volume of water evapotranspirated by the crop as a ratio of the volume of water diverted from the river or reservoirs at the inlet to an irrigation project or pumped from the groundwater [*Bos and Nugteren*, 1978]. Project efficiency is an important indicator for the individual project because withdrawal of a large quantity of water is more costly than withdrawal of a smaller one. *Seckler* [1996], however, points out that from the perspective of managing the whole water basin the drainage losses of one irrigation project can become the water supply of the next irrigation project downstream, provided that the drainage water is not polluted or reaches a sink. The more often the water is reused, the higher is the fraction of total amount of water available for withdrawal that can be used productively for crop evapotranspiration. This also entails that in a basin with an already high degree of water reuse, improved project efficiencies will not help much to increase the availability of water for new irrigated areas within the basin.

[27] Table 1 lists the project efficiencies of irrigation water use that we estimate for each of the world regions. These rough estimates are based on the project efficiency data of *Bos and Nugteren* [1978], *FAO* [1997] estimates for 84 zones in Africa, the data of *van der Leeden et al.* [1995] for Canada, the data of *Guerra et al.* [1998] for South and Southeast Asia, on the water use data of

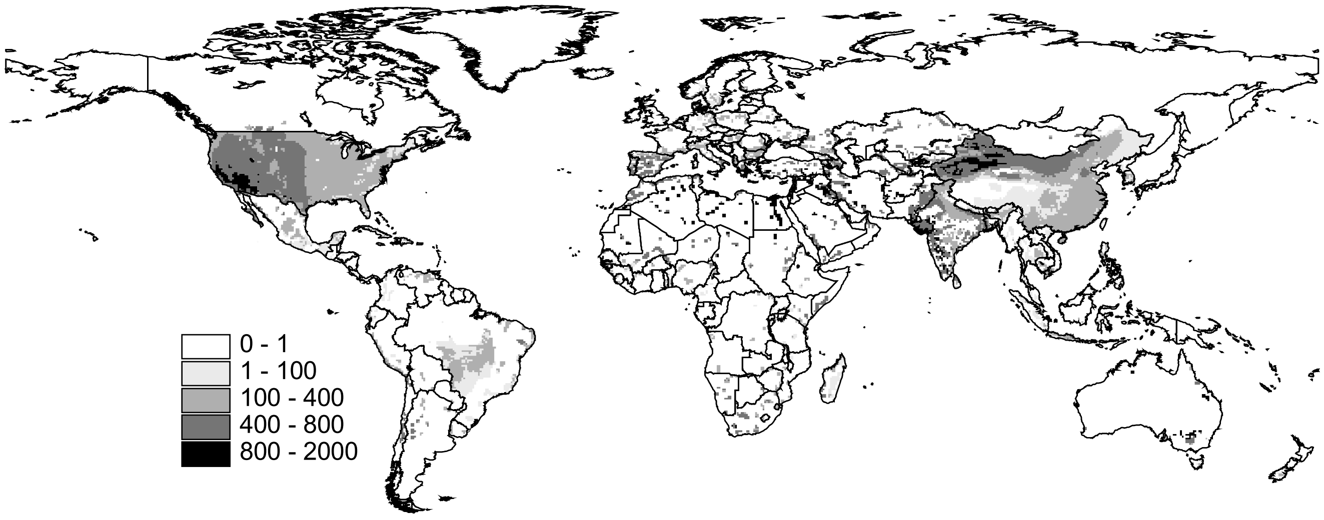

Figure 3. Net irrigation requirement per unit irrigated area, in mm/yr, under average climatic conditions (1961–1990), in grid cells with irrigated areas in 1995.

Solley et al. [1998] for the United States, and information by the Spanish National Committee of the International Commission on Irrigation and Drainage (Ortiz, personal communication, 1998) for Spain (average value for Spain used for the Organization for Economic Cooperative Development Europe South world region).

4. Results

[28] Figure 3 shows the computed annual net irrigation requirement per unit irrigated area I_{net}, under 1961–1990 long-term average climatic conditions, in all grid cells that were equipped for irrigation in 1995. In hot arid and semi-arid regions, I_{net} is more than 1000 mm/yr (1 m^3 of water per 1 m^2 of irrigated area), while in colder areas (like in Poland and Belarus) or in the humid tropics, values of less than 100 mm/yr occur. These values reflect the climate, the modeled cropping pattern, and the growing seasons. For example, if a cell is modeled to have a cropping intensity of 2, the computed I_{net} should be more than double the value that would occur with a cropping intensity of 1.

[29] In dry and hot years, I_{net} is higher than under average climatic conditions, and it is very probable that then the available water resources are less than normal. It is in these dry years that the problem of water scarcity shows most distinctly. For river basin management and the planning of new irrigation schemes, it is therefore important to take into account the conditions in typical dry years. On the basis of calculations with the climate time series from 1901–1995, we determined, for each cell, I_{net} in the so-called 1-in-10 dry year by picking the ninth highest I_{net} value that is computed for this time series. This I_{net} value will only be exceeded in 1 out of 10 years. The increase of the 1-in-10 dry year irrigation requirement with respect to the average irrigation requirement is shown in Figure 4. In general, the higher the average irrigation requirement, the lower the increase in the cell-specific 1-in-10 dry year. However, there are regional differences; for the same average values the variability is higher in North America and southern

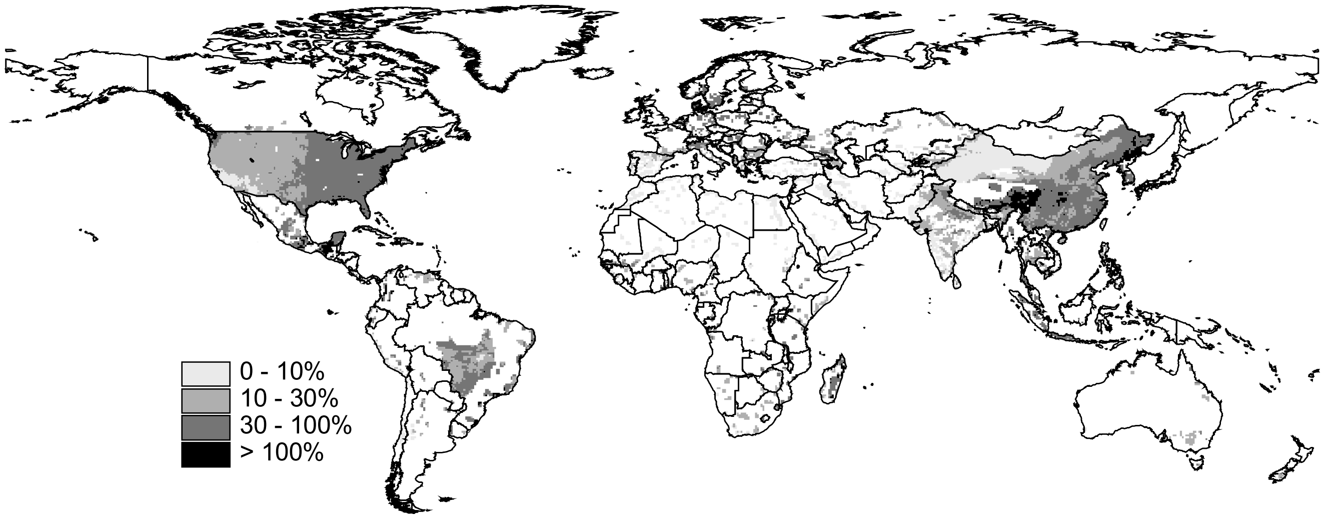

Figure 4. Increase of the irrigation requirement in a cell-specific 1-in-10 dry year with respect to the irrigation requirement, under average climatic conditions (1961–1990), in grid cells with irrigation in 1995.

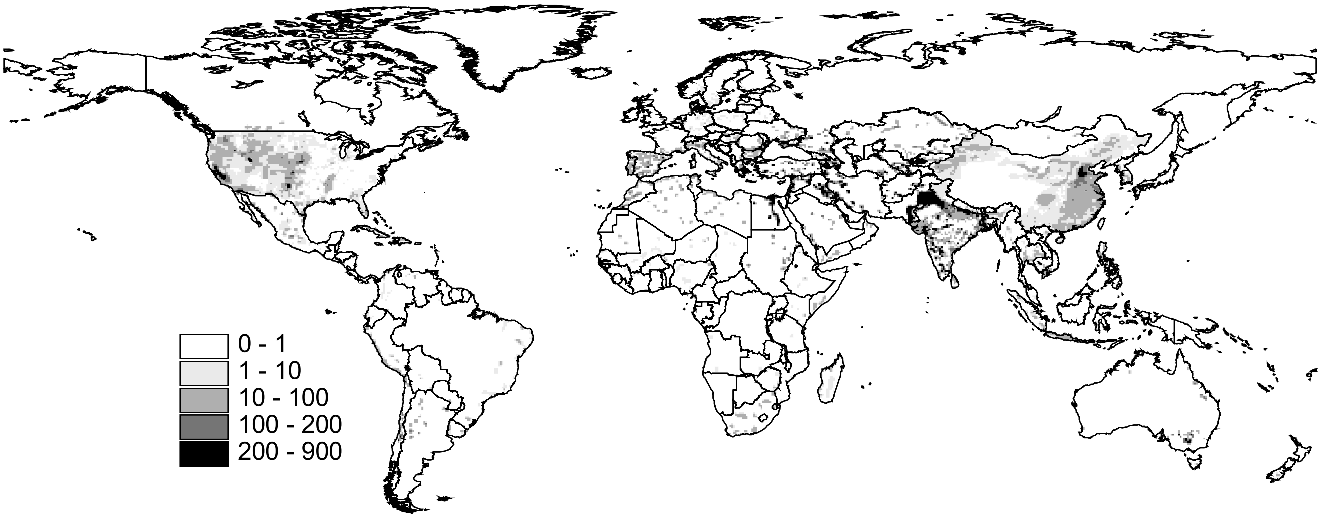

Figure 5. Net irrigation requirement per unit cell area, in mm/yr, under average climatic conditions (1961–1990), in grid cells with irrigated areas in 1995.

Africa than in Europe and northern Africa. In regions with a high average I_{net} (above 900 mm/yr), where essentially all the water the crops needs must be provided by irrigation, the increase of the requirement in the typical dry years is obviously low (e.g., in northern Africa less than 10% or 20–70 mm/yr, compare Figures 3 and 4). In regions with an average I_{net} of 300–600 mm/yr, the increase in a typical 1-in-10 dry year is more significant (e.g., in southeastern Europe, 10–30% or 60–100 mm/yr, and in the western United States, 10–30% or 90–240 mm/yr). Where the average I_{net} is between 150 and 300 mm/yr, increases of 30–50% may occur, for example in the southeast of China (corresponding to 50–150 mm/yr) or even of 50–100% (in the eastern United States, corresponding to 70–200 mm/yr). It is rather seldom that the irrigation requirement during a cell-specific 1-in-10 dry year is more than double the irrigation requirement under average climatic conditions. This occurs in regions with rather small requirements like in Japan, northeast China, and Mexico (average I_{net} 40–60 mm).

[30] Comparing the climate-dependent variability of I_{net} to that of runoff (with climate variability defined as the ratio of the respective value in a typical dry year to the value under average climatic conditions), we observe that for both variables, the variability increases with decreasing average values [*Döll et al.*, 1999]. Thus runoff variability is high in warm or dry areas, while the variability of the irrigation requirement is high in cold or wet areas. This has implications for the design of the irrigation water supply infrastructure.

[31] When the cell value of the net irrigation requirement per unit irrigated area (Figure 3) is multiplied by the fraction of each 0.5° by 0.5° cell area that was equipped for irrigation in 1995 (Figure 1), the net irrigation requirement per unit cell area is obtained (Figure 5). These values represent the total net irrigation requirement in each cell and can be directly compared with annual water availability, expressed as runoff in mm/yr. The globally highest requirements, with values of more than 500 mm/yr, occur in India, Pakistan (Indus basin), Uzbekistan, Iraq, Turkey, and Egypt. More than 300 mm/yr are reached in the United States (California and the Midwest), Greece, Romania, Iran, the southern part of the former Soviet Union, Afghanistan, Bangladesh, China (south of Beijing), and Australia (Murray-Darling Basin). In Chile, Argentina, Mexico, Spain, Italy, France, and Sudan, there are some areas with a net irrigation requirement per unit cell area of more than 100 mm/yr. Table 3 lists the net and gross irrigation requirements averaged over the world regions and the whole globe.

5. Comparison of Model Results to Independent Data

[32] Global models necessarily rely on coarse, uncertain data and a large number of model assumptions. Therefore it is particularly important to evaluate the validity of the model, which is done mainly by comparing model results with independent information on cropping patterns, growing seasons, and irrigation requirements.

[33] Table 4 lists the modeled cropping pattern, start date(s) of the growing season(s), potential (i.e., reference crop) evapotranspiration E_{pot}, crop-specific potential evapotranspiration E_{pot_c} during

Table 3. Areas Equipped for Irrigation in 1995 (A_{irr}) and Computed Average Net (I_{net}) and Gross (I_{gross}) Irrigation Requirements of World Regions

	A_{irr}, 1000 km^2	I_{net}, km^3/yr^a	I_{gross}, km^3/yr^a
Canada	7.1	2.4	3.5
United States	235.6	112.0	185.9
Central America	80.2	17.5	38.6
South America	98.3	26.6	59.1
Northern Africa	59.4	66.4	94.9
Western Africa	8.3	2.5	5.6
Eastern Africa	35.8	12.3	21.9
Southern Africa	18.6	7.1	12.8
OECD Europe	118.0	52.4	88.4
Eastern Europe	49.4	16.7	33.5
Former USSR	218.7	104.6	174.9
Middle East	185.3	144.7	241.8
South Asia	734.6	366.4	1054.8
East Asia	492.5	123.8	363.7
South East Asia	154.4	17.1	43.2
Oceania	26.1	17.7	25.3
Japan	27.0	1.3	3.7
World	2549.1	1091.5	2452

[a] Values represent irrigated areas of 1995, under 1961–1990 average climatic conditions.

Table 4. Cropping Patterns, Growing Seasons (Length 150 Days), Potential (Reference Crop) Evapotranspiration E_{pot} and Crop-Specific Potential Evapotranspiration E_{pot_c} During the Growing Season(s), and Annual Net Irrigation Requirements per Unit Irrigated Area I_{net} in Selected Grid Cells (Model Computations for Average Climate 1961–1990)

Grid Cell	First Day of Growing Season(s)[a]	E_{pot}, mm	E_{pot_c}, mm	I_{net}, mm/yr
Northern Germany, 52.75°N, 10.25°E	NR: May 19	385	321	72
NE China, 42.75°N, 125.75°E	NR: May 23	490	407	16
Western Spain, 39.25°N, 5.75°W	NR: April 11	1012	885	771
Northern Egypt, 31.25°N, 30.75°E	R/NR: April 1/Aug. 29	1639	1473	1393
	NR/NR: Feb. 15/July 15	1728	1443	
South China, 28.75°N, 115.75°E	R/NR: April 7/Sept. 4	845	762	234
SE United States, 27.25°N, 81.25°W	R: May 27	616	554	87
NE Brazil, 4.75°S, 37.75°W	R/R: Jan. 28/July 6	1102	999	252
	NR: Jan 18	520	424	
Chile, 28.75°S, 70.75°W	NR: Nov. 8	943	792	725
Southern Australia 35.75°S, 144.75°E	NR: Sept. 21	922	803	652

[a] NR is nonrice; R is rice.

the one or two growing seasons, and annual net irrigation requirements per unit irrigated area I_{net} in selected grid cells around the world. Please note that E_{pot_c} is the amount of water that the crop would evapotranspirate without moisture stress, i.e., with sufficient supply of irrigation water, and I_{net} is the fraction of E_{pot_c} that must be provided by irrigation to avoid moisture stress and thus guarantee optimal crop growth. E_{pot_c} is smaller than E_{pot} even for rice because of the assumption that during the first 30 days, only one tenth of the total irrigated area is required for the seedlings (Figure 2). In northern and central Europe, mainly potatoes, sugar beets, vegetables, and grass are irrigated. No multicropping occurs, and the actual growing seasons for potatoes and sugar beets coincide rather well with the modeled growing seasons. According to *Roth* [1993] the net irrigation requirement per unit irrigated area I_{net} in Germany is 80–110 mm/yr. The value for the cell in northern Germany (72 mm/yr) and the average value for Germany (112 mm/yr) thus appear to be reasonable estimates. In China, rice is predominantly grown in the southern part, and there, double cropping, wheat after rice, is common. This cropping pattern is represented well by the model. A comparison of the modeled I_{net} (Figure 3 and Table 4) with independent estimates for five irrigation zones in China (Ministry of Water Resources and Electrical Power, Irrigation and Drainage in China, unpublished report, Beijing, China, 1987). Showed that the model results are within the wide ranges of crop-specific I_{net} values in the five zones. According to *El Guindy et al.* [1987] the rice growing season in northern Egypt is typically from May to the beginning of October, while the modeled rice season already starts at the beginning of April (cell in northern Egypt in Table 4). The modeled growing seasons in NE Brazil, on the other hand, coincide very well with actual ones. In the United States, rice is grown in the southeast but also in California. As temperature and soil conditions are more favorable in the southeast, the rice areas in California are not simulated by the model. The same is true for the rice areas in the northwestern part of India.

[34] In only a few countries in the world, irrigation water use is known with reasonable accuracy. Table 5 provides the computed total net and gross irrigation requirements in such countries and compares them with independent data. Only for Spain and the United States were independent data of the net irrigation requirement (or, rather, consumptive water use) available. In all other cases, only the country value of the withdrawal water use for agriculture was accessible, from which we derived the equivalent of the gross irrigation requirement by subtracting the livestock water use that is computed by WaterGAP 2 for the year 1995.

[35] In the case of the data for Spain the average net irrigation requirement was calculated in each of 13 river basins (J.A. Ortiz, personal communication, 1998), while in the case of the United States, consumptive irrigation water use was collected for each county [*Solley et al.*, 1998]. Both data sources also provided the irrigated area per river basin or county, respectively. As this information was included in the global map of irrigated areas, any discrepancies in the computed net irrigation requirement and the independent data is mostly due to the irrigation model and the climate data. The net irrigation requirement for Spain is overestimated by 40%, which might be due to two reasons. First, a certain fraction of the irrigated crops is actually grown in the winter, while the temperature criterion in the model leads to a summer growing season (compare Table 4). Second, Ortiz (personal communication, 1998) noted that for the calculation, the basic plant water requirement was adjusted to actual good irrigation practices. This might indicate that the existing water scarcity

Table 5. Comparison of Computed Net (I_{net}) and Gross (I_{gross}) Irrigation Requirements (on 1995 Irrigated Areas, 1961–1990 Average Climate) with Independent Data

	Computed		Independent Data	
	I_{net}, km^3/yr	I_{gross}, km^3/yr	I_{net}, km^3/yr	I_{gross}, km^3/yr
China	120	352		405[a]
India	223	655		457[a]
Egypt	42	60		47[b]
Israel	1.2	2.0		1.3[c]
South Africa	6.1	10.9		9.5[d]
Spain	21	35	15[e]	24[e]
United States	112	186	113[f]	185[f]
World	1092	2452		2210[g]

[a] Values are from *FAO* [1999] (total for agriculture 1993; 3 km^3 for livestock).

[b] Value is from *WRI* [1998] (total for agriculture 1993; 0.08 km^3 for livestock).

[c] Value is from Y. Dreizin (Water Commissioner of Israel, personal communication, 1998) (total for agriculture 1995; 0.01 km^3 for livestock).

[d] Value is from *WRI* [1998] (total for agriculture 1990; 0.05 km^3 for livestock).

[e] Value is from J.A. Ortiz, (ICID Spain, personal communication, 1998).

[f] Values are from *Solley et al.* [1998].

[g] Values are from *WRI* [1998] (total for agriculture 1987; 25.8 km^3 for livestock).

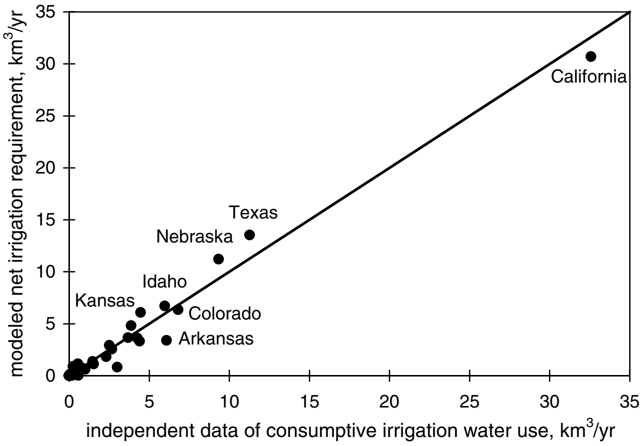

Figure 6. Comparison of computed net irrigation requirements in the U.S. states with independent data from the U.S. water use survey [*Solley et al.*, 1998].

leads farmers to irrigate less then optimal. The same two reasons might apply for Israel, where the model overestimates the gross irrigation requirement by 50%. However, when comparing gross irrigation requirements like in the case of Israel, another source of error is the irrigation water use efficiency. For Israel, the value for the Middle East of 0.6 was used. Using a more probable country-specific value of, let's say, 0.8, the overestimation of the irrigation requirement would be reduced to 15%.

[36] In case of the United States the computed and the independent values of the irrigation requirement coincide amazingly well (Table 5). In order to check if the good simulation result for the United States is due to a canceling of errors, the net irrigation requirements averaged over the individual U.S. states are compared (Figure 6). Also on the state level, the simulation results fit the independent data well, at least for states with a high net irrigation requirement. The computed and independent values are highly correlated with a modeling efficiency [*Janssen and Heuberger*, 1995] of 0.975.

[37] The gross irrigation requirements for India, Egypt, and South Africa are overestimated by the model by 44%, 28%, and 15%, respectively, while the value for China is underestimated by 13%. The computed global gross irrigation requirement is 11% higher than the data value provided by *WRI* [1998], which is representative approximately for the year 1987.

[38] It is difficult to judge the quality of the modeled irrigation requirements because the errors in the independent data listed in Table 5 are unknown but may be large. Nevertheless, the model appears to be accurate enough for continental or global modeling. We base this judgment to a large degree on the good correspondence of the model results to the independent data for the United States, which we consider to be the most reliable worldwide.

6. Summary and Conclusions

[39] The presented model of irrigation requirements is, to our knowledge, the first model to compute water requirements for irrigation on the global scale in a spatially explicit manner (0.5° resolution). On the basis of a raster map of irrigated areas the model simulates the cropping patterns, the growing seasons, and the net and gross irrigation requirements, distinguishing two crops, rice and nonrice. Modeling results are influenced by assumptions on the cropping intensity and the irrigation water use efficiency, both of which are differentiated among world regions. Using time series of monthly climatic variables from 1901 to 1995 and the global map of areas equipped for irrigation in 1995, the irrigation requirements under long-term average climatic conditions are computed, and the impact of climate variability is analyzed.

[40] Given the scarce and uncertain data on irrigation, more specifically on irrigated areas, irrigated crops, growing seasons, cropping intensities, and irrigation efficiencies, the model output is necessarily uncertain, too. However, by combining the existing data with appropriately simple concepts about cropping patterns, growing seasons, and irrigation requirements, the model generates information on irrigation requirements that have not been available before at the global scale. The accuracy of the model results can be assessed only roughly by comparing simulated cropping patterns and growing seasons to selected information on the actual rice growing areas and growing seasons and by comparing the computed net and gross irrigation requirements to independently estimated values. The simulated cropping patterns and growing seasons generally appear to reflect reality, but given the simplicity of the model, only the dominant features are represented, and some discrepancies certainly occur. It is difficult to assess how well the computed irrigation requirements represent the actual ones, as the uncertainty of published information on irrigation water use is unknown but may be high; irrigation water use is generally not measured or even registered. Comparisons of simulated irrigation requirements to independent data on irrigation water use in countries with apparently reliable information indicate that the irrigation model tends to somewhat overestimate the real water use. This might be consistent with the model approach of computing optimal water requirements and not actual (suboptimal) water uses. The good correspondence of computed irrigation requirements in the U.S. states with independent data from *Solley et al.* [1995], however, is encouraging, as we consider these data to be the most reliable worldwide. In conclusion, we believe that the presented irrigation model is accurate enough for continental or global modeling.

[41] The model can provide information on irrigation water requirements in large river basins or in countries. Globally, the computed net irrigation requirement for the 2.5 million km^2 of area equipped for irrigation in 1995 is about 1100 km^3/yr, while the gross irrigation requirement amounts to almost 2500 km^3/yr. These numbers are valid for average long-term climatic conditions. In dry years, irrigation requirements are higher. However, in contrast to the influence of climate variability on runoff, the influence of climate variability on irrigation water requirements is smallest in hot and dry countries and highest in cold and humid ones.

[42] In the future, the irrigation model will be used to assess the impact of climate change on irrigation water requirements. In combination with the hydrological model of WaterGAP, it will contribute to a better analysis of water scarcity in river basins. Any water scarcity indicator should, in our opinion, include the situation under both average and dry climatic conditions and take into account both the consumptive and the withdrawal water uses (i.e., both the net and the gross irrigation requirements). Besides, with the improved irrigation model, the complex relation between water and food security can be analyzed more reliably. For example, by coupling the water requirements of all water use sectors and the available water resources of a river basin, we will be able to estimate to what degree irrigation can be extended in the future. Finally, the computed net irrigation requirements will be helpful for checking or calibrating large-scale hydrological models and land surface modules of climate models against measured river discharges. In a few important rivers of the world, natural discharge is diminished significantly by consumptive water use for

irrigation, such that measured discharges should be corrected for the computed net irrigation requirements before they are used for comparison with computed (natural) discharges.

[43] The reliability of the model results will increase if the global raster map of irrigated areas can be improved. To this end, more detailed information on the distribution of irrigated areas within countries will be obtained. A further model improvement would be possible if better information on the types of irrigated crops, in particular on the fraction of permanent cultures, and on their growing seasons could be collected.

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