Global modelling of runoff and irrigation requirements in typical dry years

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Abstract In order to assess the impact of global change on water scarcity, it is appropriate to look at the situation not only under average climatic conditions but also in dry years. With our global model of water availability and water use in drainage basins (WaterGAP) we calculated runoff and irrigation water use under average climatic conditions and in basin-specific typical dry years. On 33% of the global land area, runoff in the meteorological 1-in-10 dry year differs from runoff in the hydrological 1-in-10 dry year by more than 10%. Besides, years with high irrigation requirements do not necessarily coincide with either type of typical dry year. Therefore, it is necessary to analyse the water situation during three types of basin-specific 1-in-10 dry years that are defined based on (a) precipitation, (b) runoff and (c) irrigation requirements.

INTRODUCTION

In order to assess the impact of global change on the problem of water scarcity, we have developed a global model of water availability and water use in drainage basins (WaterGAP). By global change, we mean climate change as well as demographic, socio-economic and technological changes. In addition, our objective is to identify sustainable water management strategies.

On the global scale, water resources and use were assessed by Seckler *et al.* (1997), Raskin *et al.* (1997), Shiklomanov (1997) and Arnell & King (1998). These studies determined country averages and assumed average climatic conditions. However, in order to evaluate the problem of water scarcity, and define critical thresholds for it, it is important to determine the water situation of drainage basins in typical dry years. Of two areas with equal conditions under average climate, the area with the higher inter-annual climatic variability will tend to have more frequent low flow years (assuming a typical lognormal distribution). In addition, in dry years, the reduced availability of water is often exacerbated by the higher than normal demand for it. This is particularly the case in the irrigation sector, which in most basins is the largest water user.

In this paper, we present a preliminary global analysis of runoff and irrigation water use in typical dry years. In particular, we show the difficulties of defining a typical dry year that can be used for a comparative assessment of water scarcity.

METHODOLOGY

WaterGAP 1.1 simulates both runoff (surface runoff and groundwater recharge) and water use (for domestic, industrial, livestock and irrigation purposes). The model

computes annual values of the respective water availability and use quantities. The global land area is represented by a 0.5° by 0.5° grid (59 831 cells). Each cell is part of a drainage basin, a country and a world region. 1162 basins of widely varying size are distinguished. A detailed model description can be found in Alcamo *et al.* (1997).

Computation of runoff and irrigation water use

The interest in hydrological modelling at the global scale is mainly driven by the need to improve climate models. Because of this, special attention has been given to land-surface parameterizations. A large variety of these parameterizations have been proposed, which lead to markedly different partitioning of precipitation between evapotranspiration and runoff (compare the results from the Project for Inter-comparison of Land-surface Parameterization Schemes, Koster & Milly, 1997). Most of these land-surface parameterizations appear to be more physically-based than most smaller-scale hydrological models because they attempt to represent the water and energy processes in a vertical column of soil and vegetation with physically-based equations; however, they assume that one such column is representative for the whole cell area. Unfortunately, few data are available for independently estimating the many required parameters. Hence these parameters need to be estimated by calibration (Schaake *et al.*, 1996). Given the scarcity of data at the global scale, the hydrological model within WaterGAP is designed as a simple conceptual model that is based on a number of independent parameter sets and contains only one calibration parameter, the runoff coefficient. For each cell, the water balance of the soil is computed daily. Although the next model version of WaterGAP will include flow routing between cells, version 1.1 calculates the runoff of a drainage basin as the average runoff of all the cells within the basin. Actual evapotranspiration is computed from potential evapotranspiration E_p, the actual soil water content within the effective rooting zone S, and the total available soil water content S_{max}, which is calculated as the product of the total available water capacity in the uppermost metre of the soil and the land cover specific rooting depth. Total runoff R is computed from effective precipitation P_{eff} (precipitation as rain plus meltwater) as:

$$R = P_{eff}\left(\frac{S}{S_{max}}\right)^{\gamma} \tag{1}$$

where γ is the runoff coefficient (calibration parameter). By adjusting γ, the hydrological model was calibrated to time series of annual discharges of 41 large rivers on all continents. We assumed that the water use did not significantly reduce the discharge. These river basins cover about 30% of the global land area. Discharge time series were provided by the Global Runoff Data Center (GRDC) (Grabs *et al.*, 1996). In six mostly semiarid river basins, the model consistently overestimated runoff, no matter how large γ was set, and a correction factor had to be introduced in order to simulate the measured runoff. The overestimation of runoff is partly due to neglecting the evaporation of swamps and reservoirs, and partly due to the fact that the measured discharge is already diminished by water withdrawals, in particular for irrigation. Based on the 35 river basins in which the calibration was successful, a coarse regionalization algorithm was deduced, and the uncalibrated drainage basins were

assigned γ values based on their average values of E_p, S_{max} and the number of days below 0°C.

The average global runoff for the period 1961–1990 (excluding Antarctica and Greenland) is computed to be 37 678 km^3 year^{-1}. This estimate is lower than estimates derived mainly from discharge measurements; it is 12% below the value given by Shiklomanov (1997) for the time period 1920–1985, and 7% below the value given by WRI (1996). When looking at individual continents, WaterGAP provides a lower runoff estimate than the other two sources for all continents except Africa and South America.

WaterGAP computes the consumptive use of water for irrigation I_c (the supplied irrigation water that is evapotranspirated) based on the percentage of the cell area that is irrigated, the climatic conditions and the cropping intensity. The influence of crop and soil type on consumptive use is neglected because it is not known which irrigated crop grows where. A growing period of 150 days is assumed in case of a cropping intensity of 1, while cropping intensities are assumed to be the same within each of the 13 world regions. The beginning of the growing period is chosen such that the annual I_c is minimal. If on a growing day, precipitation is less than potential evapotranspiration, I_c is the difference between the two. Following the US Department of Agriculture Soil Conservation Service Method (Smith, 1992), we use a corrected precipitation value, which takes into account that not all the precipitation is available to the crops.

The Food and Agriculture Organization (FAO) provides data of total irrigated area in each country. However, there were no global or continental-scale maps of irrigated areas available (except for Africa). We are therefore compiling a digital global map of irrigated areas, which is based on (a) FAO country values of irrigated area, mostly for 1995, (b) sketches of irrigated areas by Achtnich (1980), who covered most countries of the globe, and a few other authors, and (c) country-specific maps and data for subnational units in the case of a few countries with a large irrigated area. The irrigation water use presented in this paper is based on a preliminary global map of irrigated areas derived from (a) and (b). It shows the percentage of irrigated areas within each grid cell, and appears to be accurate enough to attempt a comparison of runoff and irrigation water use in large drainage basins.

Climatic input

The climatic input consists of the 1901–1995 time series of observed monthly precipitation and temperature on a grid of 0.5° × 0.5° (New & Hulme, 1998), together with average 1961–1990 monthly sunshine values. Calculations for average climatic conditions are performed by running the model from 1961 to 1990, and then averaging the results. As discussed above, for the evaluation of water scarcity it is appropriate to consider in particular the situation in typical dry years, e.g. dry years with an average return period of 10 years. In a recent study, we assessed present and future water scarcity during a typical meteorological 1-in-10 dry year (Döll *et al.*, 1998). However, we can base the definition of "dry" either on the precipitation (meteorological dry year) or the runoff (hydrological dry year). When comparing runoff to irrigation requirements, we might want to look at a meteorological dry year because precipitation governs the irrigation requirement, but also at a hydrological dry year, because we are

interested in the runoff available to fulfil the irrigation requirement. Besides, the definition of such a typical dry year depends on the spatial averaging unit (cell, drainage basin, large river basin, ...), which we chose to be the drainage basin.

For each of the 1162 basins, we computed the time series of annual precipitation and annual runoff averaged over the basin from 1901 to 1995; we then chose the year with the 9th lowest annual precipitation (or runoff) out of the 95 years, which corresponds approximately to the year with the 10-year minimum precipitation (or runoff). We also selected the meteorological driest year as well as the hydrological driest year of the period 1901–1995.

RESULTS

In typical dry years, the runoff in each basin is only a fraction of the runoff under average climatic conditions. This can be seen in Fig. 1, which shows the comparison between the runoff during the *hydrological* 1-in-10 dry year (R_h) in each basin and the long-term average runoff. In semiarid and arid areas, runoff in such a typical dry year is less than 50% of the average runoff. However, the picture for the *meteorological* 1-in-10 dry year (runoff R_m) looks different. On 33% of the global land area, R_h and R_m differ by more than 10%. On 11% of the land area, R_h is more than 30% smaller than R_m, while on 4.2%, it is more than 30% larger. The differences are partly due to different temperatures during the two types of typical dry years, and partly due to the seasonal distribution of precipitation within the year. Consider the case of year 1, with lower annual precipitation than in year 2. If more high-intensity rain storms occur in year 1, then annual runoff in year 1 might actually be higher than in year 2. Besides, the spatial distribution of precipitation within the basin can cause differences, as certain cells might even have a higher precipitation during the 1-in-10 dry year than for average climate.

Consumptive irrigation water use during the hydrological and meteorological 1-in-10 dry years is higher than under average conditions in most drainage basins, but not in all. On the one hand, this is caused by the spatial variability of precipitation within a basin (if higher than average precipitation occurs at irrigated cells). On the other hand, a low annual precipitation does not necessarily coincide with a low precipitation during the growing season. Table 1 illustrates these points by listing runoff and consumptive irrigation use in three large basins under average climatic conditions and in the hydrological 1-in-10 year and the hydrological driest year of the period 1901–1995. In all three basins, the hydrological model was calibrated against measured discharge. With respect to runoff, the Yangtse basin in China is affected least by dry years, but during these dry years, the percent increase in irrigation water use is very high. This can be mostly explained by the small per hectare irrigation use that is computed there. Note also that irrigation use in the Indus and Columbia basins does not differ much between average conditions and the 1-in-10 dry year, while runoff is decreased by more than 20%. Comparing the discharge of the Indus with the computed consumptive irrigation water use, one notices that the assumption of negligible impact of water use on discharge, which we made for the calibration of the hydrological model, was incorrect. Table 1 also shows runoff and irrigation water use of three countries, which are computed as the sum of the values of all cells belonging to the country. Different from what one would expect, irrigation use in Spain and in

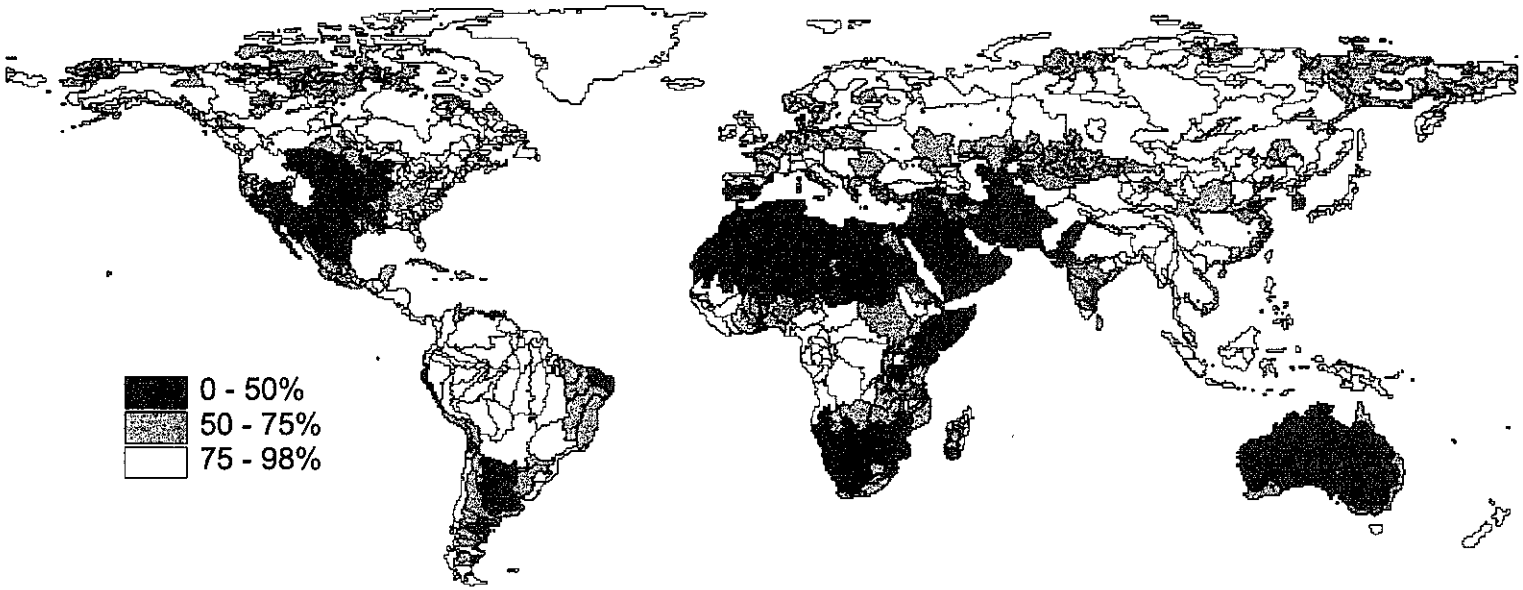

Fig. 1 Runoff in hydrological 1-in-10 dry year as a fraction of the average runoff 1961–1990, in percent. The drainage basins used in WaterGAP are shown, too.

Table 1 Discharge and consumptive irrigation water use under average climatic conditions, and in the hydrological 1-in-10 dry year and the driest year from 1901 to 1995 in three river basins and three countries.

	Yangtse	Indus	Columbia	China	Mexico	Spain
Total area (10^3 km^3)	1649	830	648	9516	2243	627
Irrigated area (% of total area)	8.6	10.4	2.8	5.2	2.7	5.6
Discharge (km^3 year^{-1}):						
Average 1961–1990	897.8	69.8	170.2	2294.1	323.9	92.1
In 1-in-10 dry year 1901–1995	808.8 (90%)	54.3 (78%)	131.3 (77%)	1947.6 (85%)	230.9 (71%)	64.9 (70%)
In driest year 1901–1995	728.9 (81%)	44.9 (64%)	113.7 (67%)	1620.0 (71%)	156.5 (48%)	42.2 (46%)
Consumptive irrigation water use (km^3 year^{-1}):						
Average 1961–1990	4.2	117.0	19.2	54.1	18.8	5.8
In 1-in-10 dry year 1901–1995	11.0 (261%)	115.5 (99%)	20.1 (105%)	73.9 (137%)	23.6 (126%)	7.7 (133%)
In driest year 1901–1995	5.6 (133%)	125.8 (108%)	22.9 (119%)	75.8 (140%)	27.2 (145%)	6.0 (103%)

the Yangtse basin in the driest year is even smaller than in the 1-in-10 dry year; this is due to the seasonal distribution of precipitation.

In order to give an impression of the relationship between the critical years that are defined either based on low precipitation, based on low runoff or based on high irrigation water use, the respective quantities are shown in Fig. 2 for the Yangtse basin

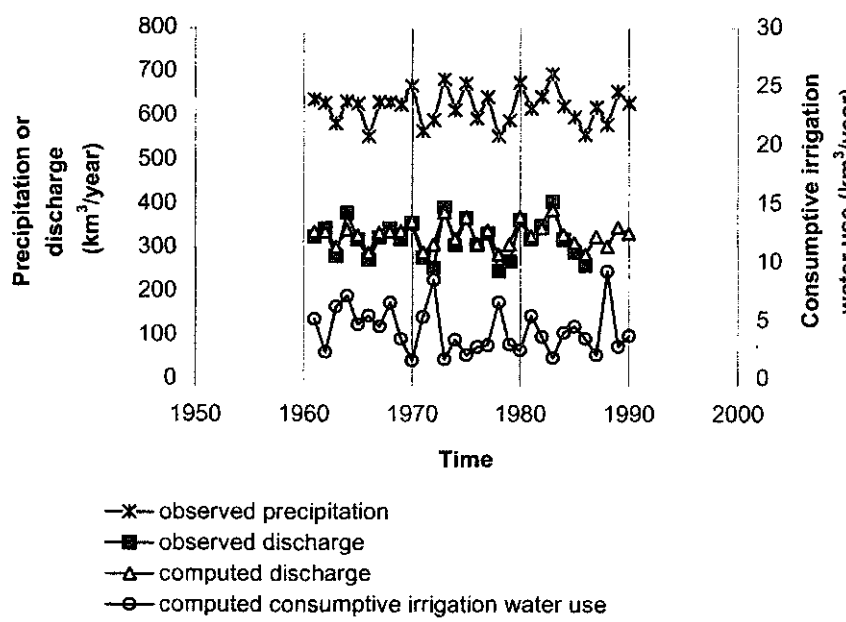

Fig. 2 Observed precipitation and discharge, and discharge and consumptive irrigation water use computed by WaterGAP1.1, in the Yangtse river basin, 1961–1990.

from 1961 to 1990. The year with the lowest precipitation was 1966, the year with the lowest observed and computed discharge 1978, while the year with the highest irrigation water use was 1988.

CONCLUSIONS

For a global comparative assessment of water scarcity, the influence of inter-annual climatic variability can be taken into account by using time series of monthly precipitation and temperature from 1901 to 1995 as input to the global water model WaterGAP. However, it is difficult to define a typical dry year that mirrors the river vulnerability of drainage basins to water scarcity (defined by a "critical" value of the ratio of water use over runoff). When comparing runoff to irrigation water requirements, it is appropriate to consider the conditions in a meteorological dry year because precipitation governs the irrigation requirement. It is also useful to look at the corresponding hydrological dry year, as it is defined based on the runoff that must be used to fulfil the irrigation requirement. However, we found that on 33% of the global land area, runoff in the meteorological 1-in-10 dry year differs from runoff in the hydrological 1-in-10 dry year by more than 10%. An even more important fact is that, due to the spatial and temporal variability of precipitation within a basin, years with high irrigation requirements do not necessarily coincide with either the basin-specific meteorological or hydrological dry year. Therefore, in order to assess water scarcity in river basins, one should analyse the water situation during three types of basin-specific 1-in-10 dry years that are defined based on (a) precipitation, (b) runoff and (c) irrigation requirements.

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