Development and testing of the WaterGAP 2 global model of water use and availability

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Abstract Growing interest in global environmental issues has led to the need for global and regional assessment of water resources. A global water assessment model called "WaterGAP 2" is described, which consists of two main components—a Global Water Use model and a Global Hydrology model. These components are used to compute water use and availability on the river basin level. The Global Water Use model consists of (a) domestic and industry sectors which take into account the effect of structural and technological changes on water use, and (b) an agriculture sector which accounts especially for the effect of climate on irrigation water requirements. The Global Hydrology model calculates surface runoff and groundwater recharge based on the computation of daily water balances of the soil and canopy. A water balance is also performed for surface waters, and river flow is routed via a global flow routing scheme. The Global Hydrology model provides a testable method for taking into account the effects of climate and land cover on runoff. The components of the model have been calibrated and tested against data on water use and runoff from river basins throughout the world. Although its performance can and needs to be improved, the WaterGAP 2 model already provides a consistent method to fill in many of the existing gaps in water resources data in many parts of the world. It also provides a coherent approach for generating scenarios of changes in water resources. Hence, it is especially useful as a tool for globally comparing the water situation in river basins.

Key words global water resources; hydrological model; integrated assessment; scenario analysis; water scarcity; water stress; water availability; water use; water withdrawals

Développement et évaluation du modèle global WaterGAP 2 d'utilisation et de disponibilité de l'eau

Résumé L'intérêt croissant pour les questions globales d'environnement a rendu nécessaire l'évaluation globale et régionale des ressources en eau. Nous décrivons un modèle global d'évaluation de l'eau, appelé "WaterGAP 2", qui consiste en deux composantes principales: un modèle global d'utilisation de l'eau et un modèle hydrologique global. Ces composantes sont utilisées pour calculer l'utilisation et la disponibilité de l'eau au niveau du bassin versant. Le modèle global d'utilisation de l'eau concerne (a) les secteurs domestique et industriel, en prenant en compte les effets des changements structurels et technologiques sur les besoins en eau, et (b) le secteur agricole, en prenant particulièrement en compte les effets du climat sur les besoins en eau pour l'irrigation. Le modèle hydrologique global calcule quant à lui l'écoulement de surface et la recharge des nappes à partir de l'estimation du bilan hydrique journalier du sol et de la canopée. Un bilan est également calculé pour les eaux libres, et l'écoulement fluvial est routé grâce à un schéma global de routage. Le modèle hydrologique global fournit une méthode évaluable pour prendre en compte les effets du climat et de l'occupation du sol sur l'écoulement. Les composantes du modèle ont été calées et testées à partir de données d'utilisation de l'eau et d'écoulement provenant de bassins versants du monde. Même si ses performances peuvent et doivent être améliorées, le modèle WaterGAP 2 est d'ores et déjà un outil consistant pour combler de nombreuses lacunes parmi celles qui existent dans les données sur les ressources en eau en de nombreux endroits du monde. Il propose également une approche cohérente pour générer des scénarios

d'évolution des ressources en eau. Par conséquent, il est particulièrement utile comme outil pour comparer globalement les situations des bassins versants.

Mots clefs ressources en eau globales; modèle hydrologique; évaluation intégrée; analyse de scénario; manque d'eau; stress hydrique; disponibilité en eau; utilisation de l'eau; prélèvements d'eau

INTRODUCTION

Although studies of water resources are typically carried out on the scale of river basin or administrative region, there is a growing demand for global-scale analyses because of new questions being posed by scientists and policy makers. For example, on the scientific side, there is keen interest in the large-scale impacts of climate change, land cover change, and other such "global change" impacts on water resources (see review in Arnell, 1996). On the policy side, governments and funding organizations are interested in assessing and setting global priorities for support of water resources development.

This interest has kindled an increasing number of global assessments of the world freshwater situation including the "World Water Vision" exercise of the World Water Commission (World Water Commission, 2000; Cosgrove & Rijsberman, 2000), the "Comprehensive Assessment of Freshwater Resources of the World" supported by a consortium of UN organizations (Raskin *et al.*, 1997), and the on-going assessments of the World Resources Institute (e.g. WRI, 2000) and the United Nations Environment Programme (UNEP, 2000). This interest raises new questions for water resource analysts and researchers: What is the current and future pressure on freshwater resources due to withdrawals from different water sectors? What river basins are under particular pressure, and how will this situation change under different scenarios of future water use? How will climate change affect the availability of water in different parts of the world? To address these questions, new analytical tools are needed for regional and global assessments of freshwater resources. This paper describes such a new tool, the WaterGAP 2 model (Water – Global Assessment and Prognosis). WaterGAP 2 is unique in that it combines the computation of water availability on the river basin scale with the modelling of water use based on dynamics of structural and technological changes in various water use sectors. The objective of this paper is to present an overview of the model, focusing on its development, calibration and testing. In a companion paper (Alcamo *et al.*, 2003), examples are presented of applying the model to current and future global water situations. This paper describes version 2.1 of the model, and is also the most comprehensive account of the model to be published. Version 1.0 of WaterGAP included much simpler representations of water use and availability and is described in Alcamo *et al.* (1997) and Döll *et al.* (1999).

The WaterGAP model is part of a growing number of approaches to global water analysis. These include, for example, the large-scale hydrology models of Arnell (1999) and Vörösmarty *et al.* (1998), discussed later in this paper. Vörösmarty *et al.* (2000) have assessed global freshwater resources in the light of climate change and population growth by combining results from a global-scale hydrology model with water demand projections (from Shiklomanov, 1997). Some global analyses of water use and availability have been carried out without the use of formal models. For example, the World Resources Institute (WRI, 1998) and Raskin *et al.* (1997) computed and compared water withdrawals and availability on the country level.

These analyses showed that increases in population and the economy in developing countries could lead to large increases in water withdrawals over the next few decades, and that withdrawals may in some cases exceed renewable water resources within a country. But the comparison of global water withdrawals and availability on the country level are very difficult to interpret because they sum together all river basins within a country—densely populated and thinly populated, very humid and very arid. In countries with wide variations in population density and climate, a comparison between country-average water withdrawals and availability is not meaningful, since water is completely transferable from one basin to another. Another drawback to comparing use and availability on the country level is the situation of international rivers, where the availability of water to a downstream country greatly depends on the inflow from another country upstream. Consequently, for meaningful results, water withdrawals and availability should be compared on the river basin or sub-basin level rather than the country level. This is the objective of contemporary global analyses as carried out, for example, by Vörösmarty *et al.* (2000), and the developers of the WaterGAP model (Alcamo *et al.*, 1997, 2000).

The WaterGAP model was developed at the Centre for Environmental Systems Research of the University of Kassel, Germany, in cooperation with the National Institute of Public Health and the Environment of The Netherlands (RIVM). The goals of the model are:

- to enable a comparison of the "freshwater situation" in different parts of the world, i.e. the uses and availability of freshwater to meet various objectives related to the requirements of society and aquatic ecosystems;
- to provide a long-term perspective (at least a few decades) on changes in global water resources.

The WaterGAP 2 model consists of two main components—a Global Water Use model and a Global Hydrology model (Fig. 1). The Water Use model takes into account basic socio-economic factors that lead to domestic, industrial and agricultural water use, while the Hydrology model incorporates physical and climate factors that lead to runoff and groundwater recharge (Fig. 1). (The term "water availability" is sometimes used in this paper and means the annually renewable water resources within a river basin, i.e. the discharge from a river basin.)
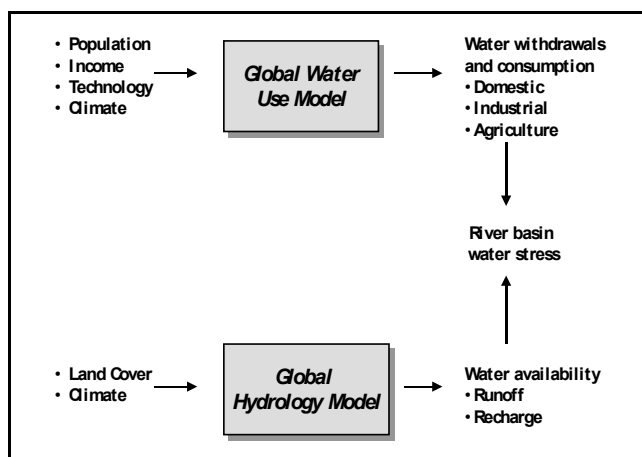

Fig. 1 Block diagram of the WaterGAP model.

The spatial scales of calculations include the country, river basin and grid scales (0.5° longitude × 0.5° latitude). The sizes of river basins can be flexibly specified in the model, since it contains a flow routing scheme based on the global drainage direction map DDM30 (Döll & Lehner, 2002). In the following sections, calculations are presented for a total of more than 10 000 "first-order" rivers (that either drain into the ocean or into inner-continental sinks) covering the entire land surface of the Earth except the ice caps. These include 3565 basins with drainage areas greater than 2500 km^2. Additionally, the 34 largest basins (with areas greater than 750 000 km^2) are further sub-divided into smaller basins.

THE GLOBAL WATER USE MODEL OF WATERGAP 2

Overview

A new approach to global water use modelling was developed for the Water Use model of WaterGAP. This model covers three water use sectors because of the availability of global data in these sectors—domestic, industry and agriculture. The domestic sector includes household use, small businesses and other municipal uses, which take high quality water directly from the municipal pipelines when it is available. The industry sector includes power plants and manufacturing facilities, while the agriculture sector covers irrigation and livestock water uses. The basic approach is to compute the water intensity (per unit use of water) in each sector and to multiply this by the driving forces of water use. For modelling purposes, the main driving forces of water use are population in the domestic sector, national electricity production in the industry sector, and area of irrigated land and the number of livestock in the agriculture sector.

The domestic and industry sectors

Model development Two main concepts are used for modelling the change in water intensity in the domestic and industry sectors—structural change and technological change. These concepts are borrowed from research on long-term trends on consumption of resources and development of technology (e.g. Grübler, 1998). They are used here because they provide a transparent, long-term and consistent view of human behaviour with regard to water use. Moreover, a water use model based on these concepts can be parameterized using proxy data that are more widely available and reliable when compared to existing global water data sets.

As employed in the Water Use model, "structural change" is the change in water intensity that follows from a change in the structure of water use (that is, the combination of water-using activities and habits within a sector). In the domestic sector, poorer households with sparse indoor plumbing may gradually acquire more water-using appliances as their income increases. Eventually, the average household becomes saturated with dishwashers, washing machines, and other water-using appliances, and as a result water use stabilizes. The consequence of these structural changes is that average water intensity of households (m^3 person^{-1}) first sharply grows along with the growth in national income, but eventually stabilizes as national income continues to
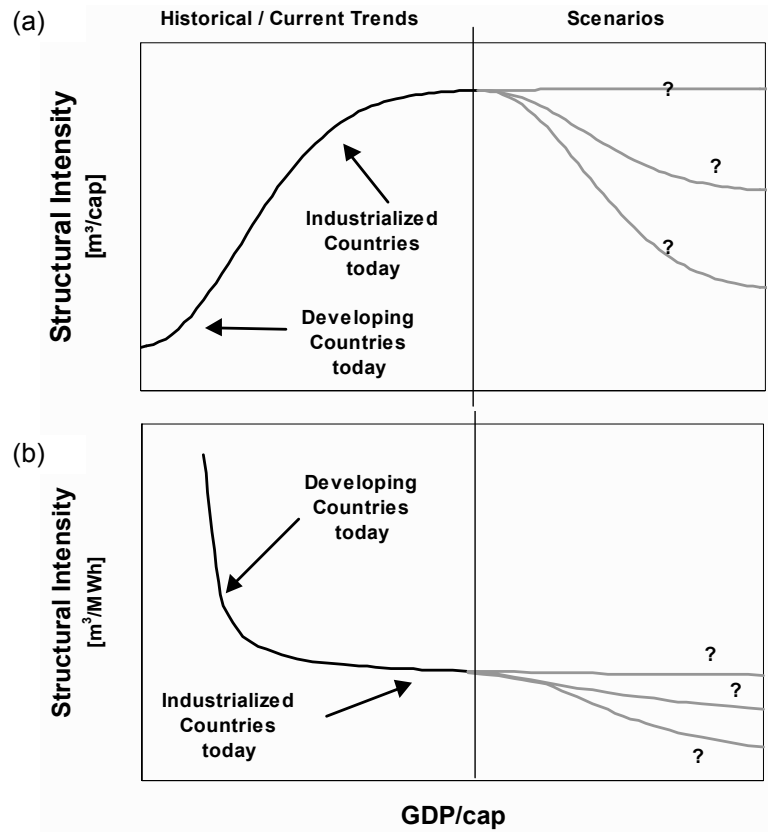
Fig. 2 Conceptual model of structural change: (a) in the domestic sector, and (b) in the industry sector.

grow. This trend is confirmed by data in Shiklomanov (2000) and from the USA (Solley *et al.*, 1998), Japan (IDI-Japan, 1997), and Germany (German Federal Statistical Agency, 1996). In WaterGAP 2 this process is represented by a sigmoid curve (Fig. 2(a)):

$$DSWI = DSWI_{min} + DSWI_{max}\left(1 - \exp(-\gamma_d GDP^2)\right) \tag{1}$$

where *DSWI* is the domestic structural water intensity (m^3 person^{-1}), and γ_d is the curve parameter (dimensionless). Values of $DSWI_{min}$, $DSWI_{max}$, and γ_d are calibrated for each region based on the trend of historical data. Where adequate data are available, the parameters are calibrated to individual countries (USA, Canada, Japan and Germany). *GDP* is the *per capita* annual gross domestic product (US\$ year^{-1}). Since *GDP* is normally specified as a function of time, equation (1) is an implicit function of time.

In the industry sector, the concept of structural change of water use represents the change in water intensity with the change in the mix of water-using power plants and manufacturers within a particular country. In richer regions, the structural water intensity has either stabilized or has a very slight downward trend. In poorer countries, the water intensity of industry first sharply decreases and then levels off with increasing national income (Fig. 2(b); Shiklomanov, 2000). The reason for the constantly high water intensities in the industry sector of poorer regions is not clear. It may arise because industrial water use is low compared to other sectors and hence industry is not strongly motivated to conserve water.

As a country develops, the electricity sector typically dominates the withdrawals of water in the industry sector and a relatively stable water intensity is reached which reflects the mix of thermal and non-thermal power plants that make up the electrical sector (Fig. 2(b)). The structural water intensity is higher where thermal plants dominate electricity production. For example, the structural water intensity in 1995 was 59 m^3 MWh^{-1} in Germany, compared to 11 m^3 MWh^{-1} in Norway where most electricity is generated by hydroelectric plants. Following these dynamics, structural changes in the industry sector are represented by a hyperbolic curve:

$$ISWI = \frac{1}{\gamma_i \left(GDP - GDP_{min}\right)} + ISWI_{min} \tag{2}$$

where *ISWI* is the industry structural water intensity (m^3 MWh^{-1}), and γ_i is the curve parameter (dimensionless). The values of γ_i and the $ISWI_{min}$ are estimated for regions or countries as in the domestic sector.

The second main concept used to model water use in the domestic and industry sectors is "technological change." While structural changes either increase or decrease water intensity, technological changes almost always lead to improvements in the efficiency of water use and a decrease in water intensity. For example, Möhle (1988) reports that the water intensity of washing machines in German households dropped 2% per year over a 15-year period. In the industry sector as a whole, technological changes were the likely cause of the 2.2% per year drop in water intensity in the US manufacturing sector between the 1950s and 1980s (Carr *et al.*, 1990). Between 1975 and 1995, the water intensity of Germany's industry sector showed a decrease of 1.9% per year (German Federal Statistical Agency, 1996) attributed mostly to technological changes. The net water intensity can be computed by combining technological and structural changes as follows:

$$IWI = ISWI \times \left(1 - \eta_i\right)^{t - t_0} \tag{3a}$$

$$DWI = DSWI \times \left(1 - \eta_d\right)^{t - t_0} \tag{3b}$$

where *IWI* is the net industry water intensity (m^3 MWh^{-1}), *DWI* is the net domestic water intensity (m^3 $person^{-1}$), and η_i and η_d are the rates of improvement in the efficiency of water use in the two sectors (% $year^{-1}$). To compute water withdrawals in the domestic sector, the *DWI* is multiplied by country population. For industry water withdrawals, *IWI* is multiplied by national electricity production. Here, electricity production is used as a surrogate for all driving forces in the sector. In reality the driving forces are both electricity production and manufacturing output, but it is not yet feasible to distinguish between these on the global level because of lack of data. Consequently, electricity generation is used because it is the dominant water user in the industry sector of most countries and because the magnitude of electricity production is a rough indicator of the magnitude of manufacturing output.

Taken together, equations (1), (2) and (3) provide a feasible approach for generating global scenarios of water use on the country scale because they do not have extensive data requirements—they require base year data and scenarios of national income, population and national electricity production. As pointed out, Shiklomanov (2000) contains the necessary global base year data, while scenario data are available from a variety of other sources (e.g. Nakicenovic *et al.*, 2000).
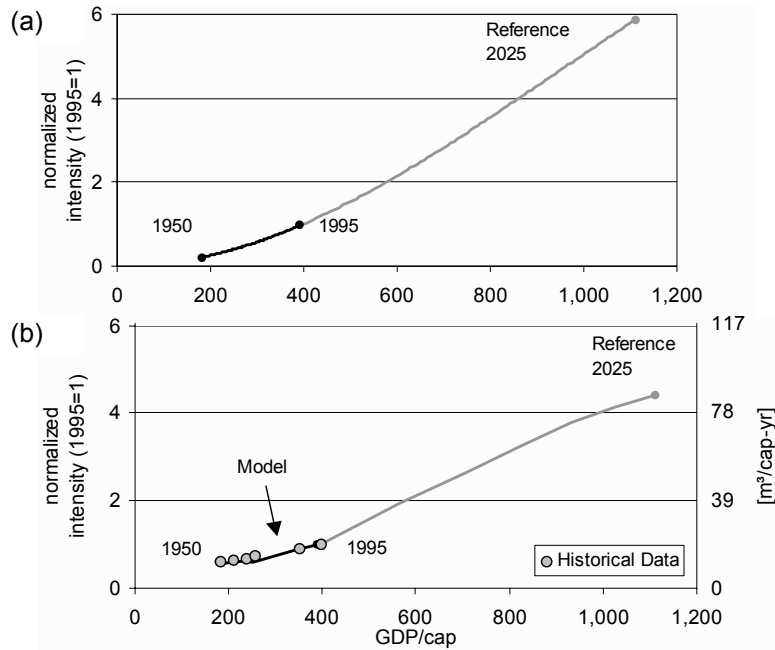
Fig. 3 Domestic water use calculations for Southern Asia (India, Pakistan, Bangladesh, Bhutan, Nepal, Sri Lanka, and the Maldives): (a) structural water intensity, and (b) net water intensity. Note that these curves are normalized. The absolute values of intensity are higher in curve (a) than in curve (b). Data points from Shiklomanov (2000).
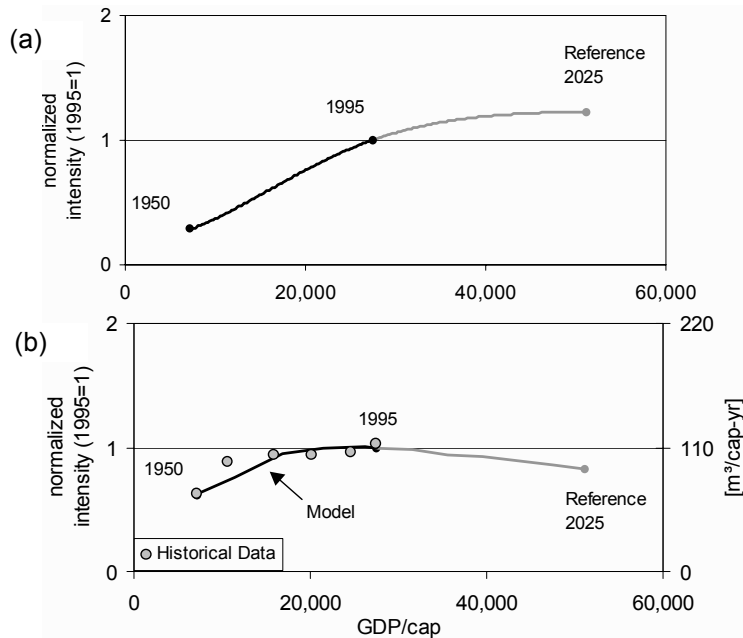
Fig. 4 Domestic water use calculations for Northern Europe (Nordic countries): (a) structural water intensity, and (b) net water intensity. Note that these curves are normalized. The absolute values of intensity are higher in curve (a) than in curve (b).

Sample calculations for the domestic sectors in Southern Asia (Fig. 3) and Northern Europe (Fig. 4) show an important contrast. These calculations are based on a reference scenario explained later in this paper. Note that the trend of structural water

intensity for Southern Asia (Fig. 3(a)) corresponds to the steep part of the curve shown in Fig. 2(a), while the data for Northern Europe (Fig. 4(a)) correspond to the flat part. This implies that in Southern Asia structural water intensity will grow sharply when *GDP* increases (as seen in Fig. 3(a)). By contrast, it may slowly increase or perhaps even decrease with growing income in Northern Europe (Fig. 4(a)). If, then, the effects of technological changes that improve water use efficiency with time are taken into account, one obtains the net water use intensities shown in Figs 3(b) and 4(b). Water intensities are then multiplied by population to obtain the country-scale withdrawals in the domestic sector.

The Appendix provides additional information about computing water use in the domestic and industry sectors.

Model testing Only a few data sets on water withdrawals in developing countries are available to test model results on the river basin scale (Table 1). For the Mekong River basin, for example, data are only available as the sum of domestic and industrial withdrawals. In other basins only the domestic sector can be compared with WaterGAP 2 calculations (since the definition of industry sector withdrawals varies greatly).

Table 1 Comparison of WaterGAP 2 and other water use estimates, in million m^3 $year^{-1}$ (contemporary mean representative for the situation in 1995).

River	Country	WaterGAP 2 (computed)	Domestic + Industry	Domestic (only)
Mekong [a]	China	342.8	315.0	n.a.
Mekong [a]	Laos	211.2	181.0	n.a.
Mekong [a]	Vietnam	2000.0	2340.0	n.a.
Mekong [a]	Thailand	1042.9	1884.0	n.a.
Rio Parnaiba [b]	Brazil	155.9	n.a.	141.4
Rio Jaguaribe [b]	Brazil	131.3	n.a.	60.9
Maipo [c]	Chile	1198.0	n.a.	536.0

[a] Data from Ringler & Rosegrant (1999).
[b] Data from Döll & Hauschild (2002) and personal communication M. Hauschild, Centre for Environmental Systems Research, University of Kassel, Germany.
[c] Data from Rosegrant *et al.* (1998).
n.a.: not available.

The calculated contributions of China, Laos, and Vietnam to the water withdrawals in the Mekong River basin agree fairly well with the available data. Considering the uncertainty of these data, calculations of Thailand's contribution are also reasonable. For two river basins in semiarid northeastern Brazil, the Parnaiba and the Jaguaribe, WaterGAP 2 slightly overestimates domestic withdrawals. A probable reason for this mismatch is that geographical distribution of income within a country, and thus of water intensity, are not taken into account by the model. Finally, the discrepancy between the computed and "measured" domestic withdrawals in the Maipo River basin, Chile, is likely to stem from the uncertainty in the estimated population distribution within the river basin: the basin itself is rather small, but the population database assumes that it contains nearly the whole population of Santiago de Chile; in contrast, the neighbouring river basin (Rapel) is assumed to be only lightly populated

and is therefore calculated to have extremely low domestic water withdrawals. In reality, probably some of the inhabitants of Santiago de Chile rely on water from the Rapel basin as well.

The agriculture sector

Model development To compute water use in the agriculture sector, an approach is used that accounts for the direct consumption of water through crop irrigation and livestock. ("Consumption" is used here to mean the volume of water that is withdrawn and then either transpires, evaporates, or percolates to deep groundwater.) In most parts of the world, livestock water use is very small compared to irrigation water use. In WaterGAP 2 the water withdrawals by livestock are assumed to be equal to their consumptive use and are computed on a global grid (0.5° × 0.5°) by multiplying the number of livestock per grid cell (GlobalARC, 1996) by their water consumption per head and year. Ten different varieties of livestock are taken into account.

The Global Irrigation model of WaterGAP 2 (Döll & Siebert, 2002) computes net and gross irrigation requirements, which reflect an optimum supply of water to irrigated plants; actual per hectare water uses may be lower due to restricted water availability. The term "net irrigation requirement" refers to the part of the irrigation water that is evapotranspired by the plants (at the potential rate), while "gross irrigation requirement" refers to the total volume of water that is withdrawn from its source. The difference between net and gross irrigation requirements arises from the losses in water that occur in delivering and distributing water for irrigation (e.g. seepage through the soil, evaporation from soil surface, losses in the delivery system). The net and gross irrigation requirements are equivalent to "consumption" and "withdrawals" used elsewhere in this paper. The ratio of net to gross irrigation requirement is called "irrigation water use efficiency". For scenario calculations this efficiency can be specified to increase with time because of technological changes in irrigation systems. This is parallel to the concept of "technological change" used above in the domestic and industry sectors.

The irrigation model uses a new digital global map of irrigated areas (Döll & Siebert, 2000) as a starting point for simulations. The model simulates the cropping patterns, the growing seasons and the net and gross irrigation requirements, distinguishing two general crop types: rice and other crops. Rice is distinguished here because data are available for the extent of irrigated rice areas (IRRI, 1988) but not for other irrigated crops.

To compute irrigation requirements, first the cropping pattern for each cell with irrigated land is modelled. The cropping pattern determines which type of crop is grown under irrigated conditions (i.e. rice, or other crops, or both) and whether the growing conditions are suitable for one or two growing seasons within a year. This is determined using a rule-based system, incorporating data on total irrigated area, long-term average temperature, 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 (Döll & Siebert, 2002). Next, for each grid cell the optimal growing season (which is assumed to span 150 days for both rice and other crops) is computed by ranking each potential 150-day period within a year according to the suitability of temperature and precipitation for crop development (taking into account the different needs at different

stages of crop development). Following this approach, the 150-day period ranked highest defines planting date and growing period in the model; for those grid cells with cropping patterns that allow two consecutive growing periods within a year, the combination of growing periods with the highest total number of ranking points determines planting dates and growing seasons in the model.

The net irrigation requirement IR_{net} (mm day^{-1}) for both rice and non-rice crops is computed for each day of the growing season as the difference between the crop-specific potential evapotranspiration ($k_c E_{pot}$) and the plant-available precipitation (P_{avail}):

$$IR_{net} = k_c E_{pot} - P_{avail} \qquad \text{if } k_c E_{pot} > P_{avail}$$
$$IR_{net} = 0 \qquad\qquad\qquad \text{otherwise}$$
(4)

The crop coefficient k_c varies between 0.1 and 1.2 depending on crop type and the growing stage of the crop. The plant-available precipitation is the fraction of effective precipitation (as rainfall and snowmelt) that is available to the crop and that does not run off; it is computed following the USDA Soil Conservation Method, as cited in Smith (1992).

This approach is similar to the CROPWAT approach of Smith (1992). The net irrigation requirements are calculated by using a time series of monthly climatic data; for the applications in this paper, data from the climate normal period (1961–1990) are used (New *et al.*, 2000). Monthly precipitation is disaggregated to daily values using a two-state Markov-chain approach that incorporates information on the number of wet days per month.

The gross irrigation requirement is calculated by taking into account regionally-varying project-level irrigation field efficiencies ranging from 0.35 in South and East Asia to 0.7 in Canada, North Africa and Oceania (Döll & Siebert, 2002).

Model testing As a test of the global irrigation model computed cropping patterns, growing seasons and irrigation requirements are compared with independent data. In most cases, model calculations come close to reality. For example, Roth (1993) esti-mated the net irrigation requirement on irrigated land in Germany to range from 80 to 110 mm year^{-1}, as compared to the average of 112 mm year^{-1} computed by WaterGAP 2. The best independent irrigation water use estimates are available for the US (for 1995, Solley *et al.*, 1998). A very good statistical agreement (modelling efficiency = 0.975) was found between WaterGAP 2 calculations and these estimates at the state level (Döll & Siebert, 2002), despite the model's failure to correctly simulate the existing rice production area in California. (The modelling efficiency is a measure of the agreement between calculations and observations that takes into account the distance from the line of perfect agreement (Janssen & Heuberger, 1995).) Despite the good agreement with these data sets, it is not expected that the model performs as well everywhere; priorities for improving model performance are dis-cussed in a later section.

Although the Water Use model for agriculture focuses on climate-related changes in water intensity, structural change also plays an important role in agricultural water use. One example is the global shift to greater consumption of meat which increases the demand for irrigated land to grow feed for livestock, and increases livestock water use. Another type of structural change is the possible shift from irrigated agriculture to

more intensive rainfed agriculture, or *vice versa*. But these structural changes cannot be directly related to changes in the water intensity of irrigation, as in the case of the domestic and industry sectors, because of the lack of time series data. Hence, structural changes are handled as scenario variables rather than as model variables.

THE GLOBAL HYDROLOGY MODEL OF WATERGAP 2

Overview

WaterGAP computes water availability on a grid and river basin scale that is consistent with available global data. The Global Hydrology model is geared towards assessing the impact of global change on water availability. It is designed to simulate the characteristic macroscale behaviour of the terrestrial water cycle, and to take advantage of all pertinent information that is globally available. A detailed description and validation of the Global Hydrology model is provided by Döll *et al.* (2003).

Based on the same time series of climatic data used to derive irrigation water use (New *et al.*, 2000), the hydrological model calculates the daily water balance of each grid cell, taking into account physiographic characteristics of drainage basins (e.g. soil, vegetation, slope and aquifer type), the inflow from upstream, the extent and hydrological influence of lakes, reservoirs and wetlands, as well as the reduction of river discharge by human water consumption (as computed by the Global Water Use model). Calculations are detailed enough to be tested and calibrated to observed discharge data. The effect of changing land cover on runoff is taken into account via its effects on rooting depth, albedo and leaf area index. The effect of changing climate on runoff is taken into account via the impacts of temperature and precipitation on the vertical water balance. For the land fraction of each cell, this balance consists of two main components: a canopy water balance determining which part of the precipitation directly evaporates from the canopy (interception), and which part reaches the soil (throughfall); and a soil water balance which partitions the throughfall into actual evapotranspiration and total runoff. The total runoff from the land area is then divided into fast surface and subsurface runoff and groundwater recharge. In addition, the water balance and storage of open water bodies (lakes and wetlands) is computed. The discharge is then routed to downstream cells.

Existing land surface parameterizations of atmospheric models and macroscale hydrological models address some but not all of the processes contained in the WaterGAP 2 Global Hydrology model:

Land surface parameterizations of climate models, with their time steps of a few hours, require a more detailed vertical resolution of the soil compartments to adequately describe the moisture and energy dynamics. Although they do not include lateral transport as in WaterGAP 2, they can be coupled with routing models (e.g. Oki *et al.*, 1999, 2001). Nijssen *et al.* (2001) applied a land surface model to compute global-scale runoff based on daily climate data from 1979 to 1993, but at a coarse resolution of only 2°, and calibrated the model against discharge time series at 22 gauging stations. Two macroscale hydrological models, with the same spatial resolution as WaterGAP 2, have been applied to the global scale and have yielded interesting results. In his analysis of streamflow in Europe, Arnell (1999) tuned model parameters uniformly across Europe but did not perform a basin-specific calibration as

was carried out for WaterGAP 2. As a result, he often obtained a 50% or higher discrepancy between simulated and observed long-term average runoff. Also, since his model does not route water from cell to cell, it is difficult to realistically simulate wetland evaporation. One difference between the approaches of Vörösmarty *et al.* (1998) and WaterGAP 2 is that they do not explicitly take into account interception. The macroscale model of Vörösmarty *et al.* (1998) was used by Fekete *et al.* (1999) to compute long-term average runoff at the global scale. They adjusted the modelled runoff by introducing a correction factor that minimizes the difference between modelled and measured discharge, rather than by calibrating model parameters. Thus, for basins with discharge measurements, the hydrological model is used for the spatial interpolation of runoff. However, the computed long-term average runoff distribution is not consistent as the time period of the climate input mostly does not coincide with the diverse time periods of available discharge measurements and because the reduction of river discharge by human water consumption was not taken into account.

Canopy water balance

Canopy storage results in partial evaporation of precipitation before it reaches the soil. In the case of a dry soil, interception leads to increased evapotranspiration. Interception is simulated in WaterGAP 2 by computing the canopy water balance as a function of the total precipitation, the throughfall and the canopy evaporation. Canopy evaporation is computed as a function of leaf area index and other variables following Deardorff (1978):

$$E_c = E_{\text{pot}} \left(\frac{S_c}{S_{c\max}} \right)^{2/3}$$

(5)

where E_c is the canopy evaporation (mm day^{-1}); E_{pot} is the potential evapotranspiration (mm day^{-1}), computed by the approach of Priestley & Taylor (1972) as used by Shuttleworth (1993); S_c is the water stored in the canopy (m); and $S_{c\max}$ is the maximum amount of water that can be stored in the canopy (m), equal to $0.0003 \times LAI$, where *LAI* is the one-sided leaf area index (dimensionless). Daily values of the leaf area index are modelled as a function of land cover (Leemans & van den Born, 1994) and climate (New *et al.*, 2000).

Soil water balance and runoff calculation

The soil water balance takes into account the water content of the soil within the effective root zone, the effective precipitation (derived from throughfall in the form of rain plus meltwater), the actual evapotranspiration, and the runoff from the land surface. Actual evapotranspiration from the soil is computed as a function of potential evapotranspiration from the soil (the difference between the total potential evapotranspiration and the canopy evapotranspiration), the actual soil water content in the effective root zone and the total available soil water capacity as:

$$E_a = \min\left((E_{\text{pot}} - E_c), (E_{\text{pot max}} - E_c) \frac{S_s}{S_{s\max}} \right)$$

(6)

where E_a is the actual evapotranspiration (mm day^{-1}); $E_{\text{pot max}}$ is the maximum potential evapotranspiration (assumed to be 10 mm day^{-1}); S_s is the soil water content within the effective root zone (mm); and $S_{s\text{max}}$ is the total available soil water capacity within the effective root zone (mm). The smaller the potential evapotranspiration from the soil, the smaller is the critical value of $S_s/S_{s\text{max}}$ above which actual evapotranspiration equals potential evapotranspiration. The term $S_{s\text{max}}$ is computed as the product of the total available water capacity in the uppermost metre of soil (Batjes, 1996) and the effective root zone related to land cover.

Total runoff is computed as a function of effective precipitation P_{eff}, S_s, $S_{s\text{max}}$, and a calibrated runoff factor, following the approach of Bergström (1994):

$$R_l = P_{\text{eff}} \left(\frac{S_s}{S_{s\,\text{max}}} \right)^{\gamma_r} \tag{7}$$

where R_l is the total runoff from land (mm day^{-1}); P_{eff} is the effective precipitation, i.e. the throughfall (precipitation dripping off the canopy or not intercepted by vegetation) plus snowmelt as computed by a simple degree-day algorithm (mm); and γ_r is a calibrated runoff factor (dimensionless). With this approach, runoff increases with increasing soil wetness, an effect that is also achieved by models representing the sub-grid variability in soil water capacity (e.g. by the VIC model of Liang *et al.*, 1994, and the Macro-PDM of Arnell, 1999).

Total runoff is partitioned into fast surface and subsurface runoff and slow ground-water runoff (or baseflow) based on rules that take into account cell-specific slope characteristics, soil texture, hydrogeology and the occurrence of permafrost and glaciers (Döll *et al.*, 2002).

Flow routing scheme

Within each grid cell, the total runoff produced within the cell and the volume of water coming from the cell upstream is transported through a series of linear and nonlinear retention storages representing the groundwater, lakes, reservoirs, wetlands and the river itself. The evaporation from open water bodies as designated in the WaterGAP 2 digital map of lakes and wetlands (which also includes large rivers) (Lehner & Döll, 2001) is computed by applying the Priestley & Taylor (1972) formulation. Then, the total cell discharge is routed according to the newly developed drainage direction map DDM30 (Döll & Lehner, 2002) to the next downstream cell, where it can evaporate in wetlands or lakes. The DDM30 scheme describes the estimated flow routing between approximately 67 000 grid cells representing the total land surface of the Earth (except Antarctica) and is based on various digital and analogue continental drainage and elevation maps. The cells are connected to each other by their respective drainage direction and are thus organized into drainage basins. Each cell can drain into only one of the eight neighbouring cells.

Calibration and regionalization

The Global Hydrology model was calibrated against annual discharges, measured at 724 stations, by adjusting the runoff coefficient γ_r (equation (7)). These basins cover

most of the world's densely populated regions or approximately 50% of the global land area (except Antarctica and Greenland). The runoff coefficient is assumed to be the same in all cells between two discharge gauges. Time series of monthly measured discharges were provided by the Global Runoff Data Center (GRDC, 1999), and covered different periods. Therefore, the model was calibrated to annual flows from the last 30 measurement years (or fewer years, depending on data availability).

The calibration goal was to limit the difference between modelled and measured long-term average discharge over the calibration period to 1%. However, in only 385 basins, this goal could be reached by adjusting the runoff coefficient within the physically plausible range of 0.3 and 3. (Note, although the coefficient can have a value greater than 1, the term $(S_s/S_{s\ max})^{\gamma r}$ mathematically cannot exceed 1.) In 201 basins, discharge would be underestimated without the introduction of one or two correction factors for runoff and discharge. This mainly occurs in snow-dominated areas where precipitation is very likely to be highly underestimated due to the measurement errors for amount of snow (Döll *et al.*, 2003). In the other 138 basins, which are often located in semiarid or arid regions, discharge would be overestimated without correction. This is due to processes such as river channel losses and evaporation of runoff from small ephemeral ponds which are not included in the hydrological model.

Runoff coefficients for the remaining uncalibrated river basins were estimated using a multiple linear regression approach. The runoff coefficients from 311 selected calibration basins were found to be correlated to three basin-specific parameters: (a) the 1961–1990 average temperature, (b) the area of open freshwater as a ratio of the total basin area, and (c) the length of non-perennial river stretches. A corrected R^2 of 0.53 was obtained for this correlation which is then used to set the runoff coefficients in the uncalibrated basins.

Validation and comparison of calculations

For validation, the annual discharge values computed at the 724 calibration stations for the respective calibration periods are compared to measured values. While the model is calibrated only to long-term average discharge, Fig. 5 presents the modelling efficiency with respect to annual discharge values and shows the capability of WaterGAP 2 to simulate the sequence of wet and dry years. The modelling efficiency calculated here (see Janssen & Heuberger, 1995), often referred to as the "Nash-Sutcliffe coefficient" in the hydrological literature, is used to relate the goodness of fit of the model to the variance of the measurement data. Different from the correlation coefficient, it indicates high model quality only if the long-term average discharge is captured well. In most of Europe and the USA, modelling efficiency is above 0.5 (which is a satisfactory value), and for many basins, it is even above 0.7. All the basins in China and most of the Siberian basins show values higher than 0.5, while the situation is mixed in the rest of the world. Figure 6 illustrates the agreement between simulated and observed annual discharge for river basins with different modelling efficiencies. In general, the likelihood of a good model efficiency is higher for basins that did not require a runoff correction.

Besides, computed long-term annual average water availability is compared to literature estimates or measured discharges. This is done for river basins (Table 2) and
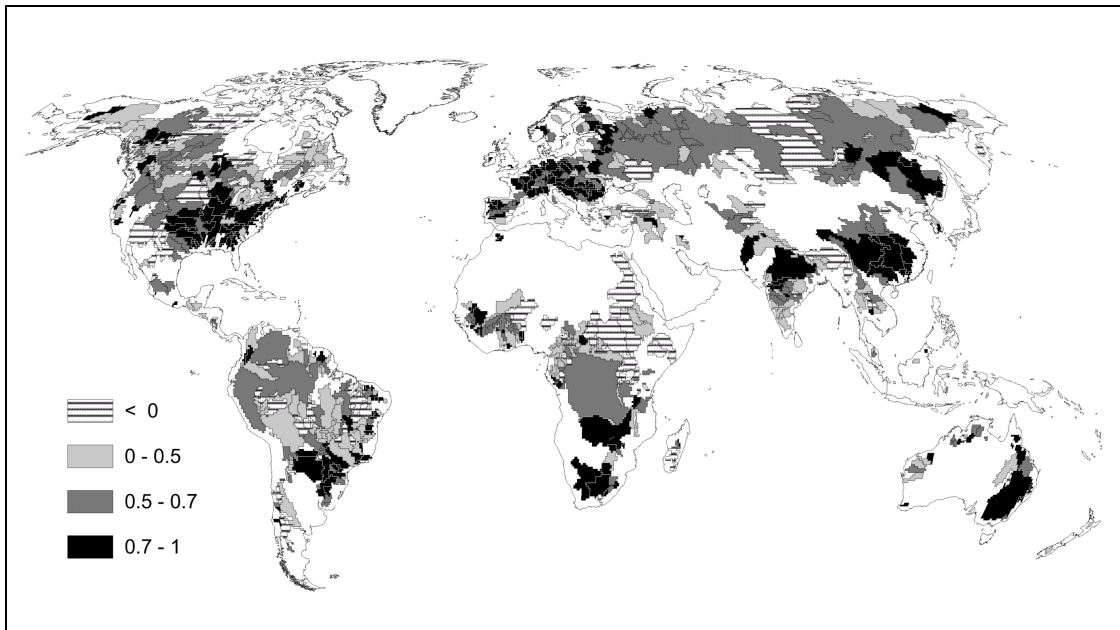
Fig. 5 Modelling efficiency for annual discharges at 724 calibrations stations (for the respective calibration periods).
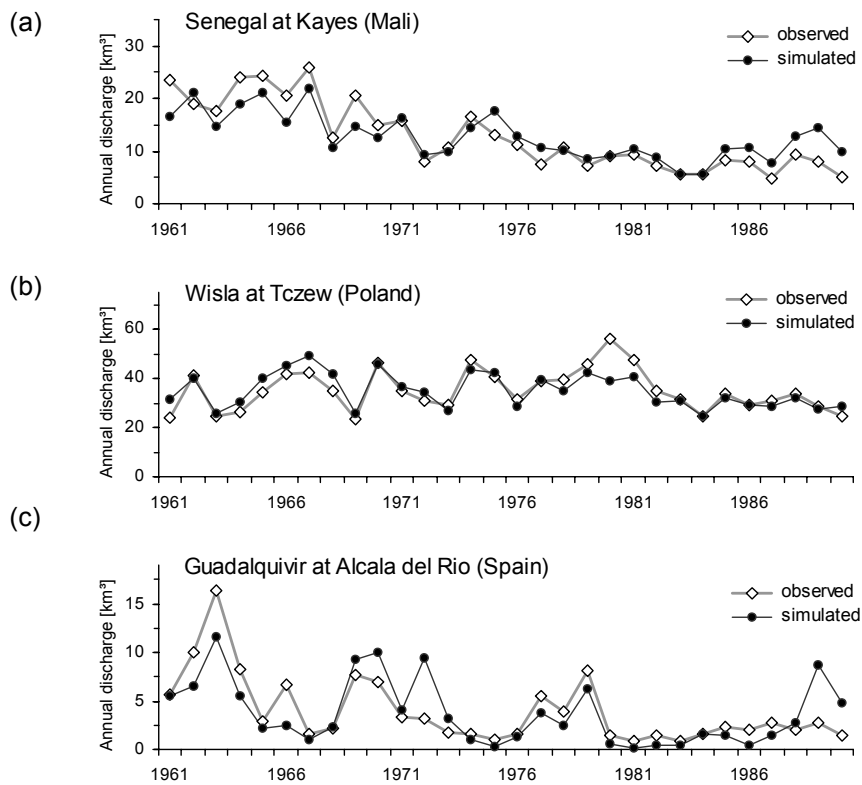
Fig. 6 Comparison of computed and measured discharge of three selected river basins: (a) Senegal (modelling efficiency = 0.73), (b) Wisla (modelling efficiency = 0.65), and (c) Guadalquivir (modelling efficiency = 0.16).

Table 2 Comparison of computed and observed long-term average river discharges of selected river basins, in km^3 year^{-1}.

River	Station	WaterGAP 2 [a] (computed)	GRDC [b] (1995)	Probst & Tardy (1987) /Period of data		Vörösmarty *et al.* (1996) [c]
Danube	Orsova	185 [d]	177	172	1840–1975	
Missouri	Hermann	58 [d]	76	72	1898–1983	
Ohio	Metropolis	201 [d]	239	234	1928–1983	
Dvina	Ust Pinega	92 [e]		106	1882–1969	
MacKenzie	Norman Wells	279 [e]				264
Xijiang	Wuzhou 3	165 [e]				224
Amazon	Obidos	5436 [f]	5463	4729	1928–1975	
Ganges	Hardinge Bridge	357 [f]	349			
Mekong	Mukdahan	233 [f]	233	262	1925–1968	
Mississippi	Tarbert Landing	442 [f]	464			
Nile	El Ekhsase	36 [f]	39			
Volga	Volgograd	240 [f]	236	257	1879–1975	

[a] average 1961–1990.
[b] average of latest time period available, max. 30 years.
[c] period of data: MacKenzie 1966–1984, Xijiang 1976–1983.
[d] uncalibrated sub-basin, part of calibrated major basin.
[e] regionalized basin.
[f] calibrated basin.

Table 3 Comparison of estimated long-term average river discharge (internal renewable water resources) of selected countries, in km^3 year^{-1}.

Country	WaterGAP 2 [a]	World Resources Institute (1998) [b]	Shiklomanov (2000)	Others
Brazil	5507	5190	6220	
Canada	2772	2850	3290	
China	2164	2800	2700	
Congo, DR	877	935	989	
India	1391	1850	1456	
Indonesia	2384	2530	2080	
Mexico	357	357	345	
Russian Federation	3348	4313	4053	
South Africa	46	45	52	
United Kingdom	193	71	108	201 [c]
United States	1984	2459	2900	1928 [d]

[a] average 1961–1990.
[b] time range not specified.
[c] USGS (1990, p. 125).
[d] van der Leeden (1975, p. 87).

countries (Table 3). The results for river basins have to be judged differently for the following cases:

Case 1. For some river basins the hydrological model of WaterGAP 2 was calibrated against the discharge at the measurement station for which the comparison was made.

Case 2. For other river basins the model was calibrated against the discharge at a station further downstream of the station for which the comparison was made.

Case 3. In still other river basins, no calibration was possible because of the lack of data.

In Case 1, discrepancies between computed and observed discharges should be relatively small and are due mainly to the different time periods. Indeed the WaterGAP 2 calculations presented in Table 2 (marked with an "f" superscript) show the close agreement of model and measurements for this case. In Case 2 (calculations marked with a "d" superscript in Table 2), discrepancies might be much higher because calibration parameters are scale- and domain-dependent. Case 3 (calculations marked with an "e" superscript in Table 2) is the most difficult test for the model, as discharge is computed without any basin-specific information on actual discharge.

Table 3 demonstrates the large difference between various estimates of overall discharges on the country level. These differences may stem from different allocations of the discharge of boundary rivers to countries or different interpretations of inner-continental sinks and their evaporation. The uncertainty of the discharge computed by WaterGAP 2 is deemed to be of the same degree as that of other estimates.

DISCUSSION AND CONCLUSIONS

Although the WaterGAP 2 model takes some preliminary steps toward the global analysis of water resource problems, work is needed to improve its approach. For the Global Water Use model there is an urgent need for developing historical data sets of sectoral water use in different countries for checking and improving model calculations. In the domestic and industry sectors there is a need to improve the algorithm for allocating country-scale calculations to the river basin scale. An urgent task, specifically for the industry sector, is to sub-divide this sector into water uses for manufacturing and for electricity production. This requires the development of a reliable global map of power plant locations and types. A number of changes could also improve the calculations of water requirements for irrigation including: (a) improving the estimation of the extent and location of irrigated areas, (b) distinguishing between several crop types (at present, only rice and other crops are distinguished), (c) improving the estimation of evapotranspiration, and (d) better estimating the field efficiency of irrigation.

An important task for the Global Hydrology model is to improve the reliability of computed monthly flows so that better estimates can be made of critical low and high flow conditions. In particular, estimates of baseflow, evapotranspiration, and snowmelt need to be improved. Furthermore, it is also necessary to improve the computation of the water balance of wetlands and lakes and to implement better data for land use and land cover.

To reduce the uncertainty of computing water availability, it is necessary to take into account fossil groundwater reserves that are, or could be, exploited. Likewise, a method is needed to take into account current and future use of desalination as a source of freshwater in coastal regions.

After these and other improvements, WaterGAP 2 can serve as a better tool for global analysis of water resources. But as it currently stands, Water GAP 2 can already be used to compare river basins globally according to a flexible variety of indicators such as total water withdrawals, total water availability (resulting discharge from river basins) and the ratio of withdrawals to availability. As a tool for scenario analysis, it

provides a method for linking population and economic scenarios with long-term changes in water use. Examples are given in Alcamo & Henrichs (2002), Alcamo *et al.* (2000, 2003), Döll *et al.* (2003), and Henrichs *et al.* (2002). These scenarios can provide insight into future "hot spot" problem areas which could then be studied more closely with detailed models (e.g. Alcamo & Henrichs, 2002). Elsewhere, it is shown that WaterGAP 2 can be used to analyse the global impacts of climate change on river discharge (Alcamo *et al.*, 2000) and on irrigation water requirements (Döll, 2002). Although no single model can cover the wide range of scientific and policy questions posed about global water resources, WaterGAP 2 can help address some of these questions from the global perspective.

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APPENDIX: ADDITIONAL INFORMATION ABOUT COMPUTING DOMESTIC AND INDUSTRY WATER USE

Overview of procedure

Water uses in the domestic and industry sectors are first computed on the country scale because consistent global data are only available on this level. Country-scale water use is then allocated to grid cells based on the rules described below. After allocation, grid cells are re-aggregated to the river basin scale. All grid calculations in WaterGAP 2 are carried out on a global grid of 0.5° latitude × 0.5° longitude.

Procedure for country-level water use

Base year (i.e. 1995) country data are available from Shiklomanov (2000), but there are few time series data available for countries. Hence, a model is needed for calculating historical water use in most countries. A model is also needed for country-scale scenario calculations. Since country-scale data are not available for calibrating the structural change model (equations (1) and (2)) it is calibrated instead to regional data (available from 1950 to 1995) derived from Shiklomanov (2000). These data are derived by subtracting out an estimate of the improvement in water efficiency from historical trend in water intensity. The rate of improvement of water efficiency is assumed to be 2% per year, based on data from several references (e.g. Möhle, 1988; Carr *et al.,* 1990; German Federal Statistical Agency, 1996). Equations (1) and (2) are then fitted to the derived data. For industrialized regions these data are sufficient for calibrating all of the parameters in equations (1) and (2). However, the historical trends of most developing regions fall on the lower left side of Fig. 2(a), which means that a saturation value of the curve (parameter $DSWI_{max}$) is not defined. In these regions, a saturation value mid-way between the values of the United States and Europe is assumed.

Using the above procedure regional curves of structural intensity have been derived. Water intensity is now computed for individual countries: First the curves for country structural water intensity are computed by scaling each country's water intensity in 1995 with the appropriate regional curve. Next, the effect of technological change is subtracted from the computed curve of structural water intensity by assuming a rate of improvement in water efficiency η_d or η_i (specified in % year^{-1}) in equations (3a) and (3b). The resulting curve gives an estimate of the actual water intensity in the domestic sector on the country scale as a function of *GDP* per person.

To prevent the domestic water intensity from falling below a reasonable minimum, a minimum intensity of 80 l per person and day or 29.2 m^3 per person and year is set. This is about 50% of current (1995) domestic water intensity in Germany, and is close

to the average European level of 1950. It is also close to the water use for a "fair level of domestic supply" (100 l person^{-1} day^{-1}, or 36.5 m^3 person^{-1} year^{-1}) suggested by Falkenmark & Lindh (1993). Similarly, a minimum of 3.5 m^3 MWh^{-1} is set for the industry sector for industrialized countries. This value is close to Israel's current industry water intensity of 3.2 m^3 MWh^{-1}, which is considered to be very low.

The computed water intensity is then multiplied by a scenario of population in the domestic sector and by a scenario of national electricity generation in the industry sector to obtain the total water withdrawals per country.

Procedure for allocation to grid cells

Domestic withdrawals Country-level withdrawals are allocated to different grid cells based on the population density (van Woerden *et al.*, 1995), the ratio of rural to urban population of each grid cell, and the percentage of population with access to safe drinking water (WRI, 1998). Downscaling of urban population to the grid level is accomplished by first assuming that the rural population density in each grid cell of a country is the same. Next, if such assumed rural population is larger than the given total population of the cell, then the surplus is distributed equally among the other grid cells in the country.

The water use of all grid cells within a particular river basin is then summed to obtain the total domestic water use in the river basin.

Industry withdrawals Industry withdrawals are apportioned to different grid cells within a country in proportion to their urban population.