World Water in 2025

Global modeling and scenario analysis for the World Commission on Water for the 21st Century

Joseph Alcamo · Thomas Henrichs · Thomas Rösch

University of Kassel
Center for Environmental Systems Research
Kurt-Wolters-Straße 3 · 34125 Kassel · Germany
Phone +49.561.804.3266 · Fax +49.561.804.3176
cesr@usf.uni-kassel.de · Http://www.usf.uni-kassel.de

University of Kassel

GhK

Center for Environmental Systems Research

Cover photograph reproduced with kind permission of the International Hydrological Programme (UNESCO)

KASSEL WORLD WATER SERIES · REPORT No 2

World Water in 2025

Global modeling and scenario analysis for the World Commission on Water for the 21st Century

Joseph Alcamo, Thomas Henrichs, Thomas Rösch

Center for Environmental Systems Research
University of Kassel

February 2000

The Kassel World Water Series

Report No 1 – A Digital Global Map of Irrigated Areas
Report No 2 – World Water in 2025

World Water in 2025
Kassel World Water Series. Report Number 2

Report A0002, February 2000

Center for Environmental Systems Research,
University of Kassel, 34109 Kassel, Germany
Tel. 0561 804 3266, Fax. 0561 804 3176
Internet: http://www.usf.uni-kassel.de

Please cite as:
"Alcamo, J., Henrichs, T., Rösch, T. (2000): World Water in 2025 – Global modeling and scenario analysis for the World Commission on Water for the 21st Century. Report A0002, Center for Environmental Systems Research, University of Kassel, Kurt Wolters Strasse 3, 34109 Kassel, Germany."

World Water in 2025:
Global modeling and scenario analysis for the World Commission on Water for the 21st Century

Joseph Alcamo, Thomas Henrichs, Thomas Rösch

Executive Summary

The World Commission on Water for the 21st Century has prepared a set of scenarios that describe several possible developments in the world water situation by 2025. In this report we present one source of input to these scenarios – namely, a detailed scenario analysis of the world water situation, carried out with the WaterGAP global water model. This scenario analysis gives a global picture of water availability and water use on the river basin level, and identifies the river basins where renewable water resources will be under particularly heavy stress.

An important finding of the Business-as-usual (BAU) scenario is that the great contrast in the water situation between industrialized and developing countries is likely to continue. Water withdrawals in most industrialized countries decline and therefore the pressure put on water resources also declines. Meanwhile, withdrawals grow in most developing countries and increase the pressure on their water resources. Between 1995 and 2025 the areas affected by "severe water stress" expand and intensify, growing globally from 36.4 to 38.6 million km^2. The number of people living in these areas also grows from 2.1 to 4.0 billion people. The increase is especially significant in Southern Africa, Western Africa, and South Asia. In river basins under severe water stress there will be strong competition for scarce water resources between households, industry and agriculture. Moreover, the BAU and other scenarios examined here imply that the current serious water situation could continue at least through 2025. Such widespread and continuing stress on water resources increases the risk that simultaneous water shortages might occur around the world and even trigger a kind of global water crisis.

Another important finding of the BAU scenario is that future industrial and economic growth in regions under severe water stress may be limited by heavy competition with municipalities and agriculture for scarce water resources. Furthermore the BAU scenario shows that many of the world's internationally shared river basins will be in the high or very high stress categories in 2025. Indeed, 33 % of the total area of international river basins will be in either one of these categories. The competition for these water resources could be an ongoing source of tension between nations.

The preceding results are based on the assumption that a river basin is under "severe water stress" if its criticality ratio (annual withdrawals over availability) is greater than 0.4. We show through sensitivity analyses that results based on this threshold are fairly robust. But the effect of severe water stress will be different in different countries. In industrialized countries water is often treated before it is sent on to downstream users, and industry recycles its water supply fairly intensively. For these and other reasons industrialized countries can often heavily utilize their water resources (as indicated by a criticality ratio of greater than 0.4) without negative consequences. By comparison, wastewater in developing countries is usually not treated, and industries do not recycle their water supplies as often. Hence, intensive use of water here can lead to the rapid degradation of water quality and quantity for downstream users, and frequent and persistent water emergencies.

Two alternative scenarios to the BAU scenario – the "Technology, Economics, and Private Sector" scenario (TEC), and the "Values and Lifestyles" scenario (VAL) – focus on water conservation and make very strong assumptions about policies and behavior that significantly reduce the intensity of water use. One important feature of these scenarios is that they result in important breaks in current trends. First of all, every developing country achieves a minimum domestic water use adequate to meet basic needs (40 l per capita per day). Second, water withdrawals drop very sharply in industrialized countries (compared to the BAU scenario) and the pressure on water resources in these countries is also greatly reduced. Finally, under the VAL scenario, water withdrawals in developing countries stop growing even though their economies and material well-being grow tremendously.

The second important feature about the TEC and VAL scenarios is that some current trends may continue under these scenarios. For example, total water withdrawals continue to grow substantially in many parts of Africa, Latin America and Asia because of increasing population, and because of economic growth and the material aspirations that come with it. This, however, does not lead to a large increase in the areas under severe water stress in Africa and Latin America because this growth occurs mostly in water-rich areas. In these regions the problem may not be water shortages, but instead the need to rapidly expand water infrastructure to accommodate increasing water demands.

While some current trends continue under the TEC and VAL scenarios, these scenarios are still basically on the path to more sustainable water use. By contrasting them with the unsustainable trends in the BAU scenario, we have learned that improvements in water use efficiency can help to significantly lower the withdrawals of water for households and industry, and to stabilize withdrawals in agriculture. But we also learned that efficiency improvements are necessary, but insufficient to avoid on-going severe water stress in many river basins around the world. This is because population and economic growth increase the demand for water and partly counteract improvements in water use efficiency. Hence, not only efficiency improvements, but also basic structural changes (such as shifting from power plants that require water cooling to those that do not) will be needed to substantially reduce withdrawals for households and industry.

What is needed to achieve a sustainable water world? The core issue is the amount of water used for irrigation, because this is and will continue to be the principal user of water in most water-short areas of developing countries. As in the case of the domestic and industrial sectors, even rapid improvements in water efficiency will not avoid water scarcity. Apparently, fundamental "structural" changes are also needed in the world's agricultural system – These could include:

- *Slowing down the trend towards excessive meat-consumption in order to slow the growth of irrigated land needed for livestock feed.*
- *Shifting, where possible, from irrigated crops to rainfed crops.*
- *Moving irrigated farmland from river basins under severe water pressure to those richer in water. This may require a shift in the type of crops that are grown and a willingness to pay for the implicit value of water in agricultural products.*

Of course, these will not be easy actions to undertake, but they may be necessary to address current and future water scarcity.

Nomenclature

Scenarios:
BAU = **B**usiness-**a**s-**U**sual scenario
TEC = **Tec**hnology, Economics, and the Private Sector scenario
VAL = **Val**ues and Lifestyle scenario

Other terms:
CR = Criticality ratio

1. Introduction

Is water a local or a global issue? On one hand it seems very much like a local issue – If a river or aquifer is contaminated by municipal or industrial sewage, the contamination can usually be cleaned up by local wastewater control. And if the local water supply from a river is too unreliable during particularly dry months, then a reservoir can be built upstream to regulate the supply. On the other hand in our interconnected world, water users in one river basin are strongly linked to users around the world. A good example is the world food market which affects the amount and type of crops grown on irrigated fields around the world. Hence, the use of water for irrigation within a watershed will be shaped by a market that extends far beyond its borders. The point is that not only local, but also regional and global forces have an important influence on the use of water and level of water scarcity within a river basin. For that reason a global perspective is needed when assessing the world water situation. This perspective has been taken by the World Commission on Water for the 21st Century[1] (referred to afterwards as "the Commission").

Since 1998 the Commission has been preparing recommendations for the development of world water resources. These recommendations are aimed at governments, institutions, and citizen groups, and will be presented in March, 2000 at the Second World Water Forum in the Hague. The recommendations will be partly in the form of global scenarios which are being prepared by the Scenario Panel of the Commission. These scenarios consist of "storylines" or narratives that describe conceivable future developments of the world water situation. This paper presents the quantification of global water scenarios prepared as part of the work of the Commission. In this paper we take the quantitative and qualitative information in these storylines and convert them into inputs to a global water model, and compute the resulting level of stress on water resources from water use.

The global model we use for the scenario analysis is called the "WaterGAP" model, and it is the first global model that computes both water use and availability on a river basin level. In this paper we first describe the WaterGAP model, then report on results of a "Business-as-usual" scenario, and a set of alternative scenarios.

[1] The activities of the World Commission on Water for the 21st Century are described on http://watervision.org

2. Methodology

The WaterGAP model (Water – *G*lobal *A*ssessment and *P*rognosis) was developed at the Center for Environmental Systems Research of the University of Kassel, with assistance from the National Institute of Public Health and the Environment of the Netherlands. The goal of the model is to provide a scientific-based overview of global water resources from a long-term perspective. WaterGAP is based on a class of environmental models called "integrated" models which were first developed during the 1980s to study large-scale environmental problems. These models aim to couple different disciplines in a single integrated framework, and to link science with policy.

The Water GAP model consists of two main components – a Water Use model and a Water Availability (or Hydrology) model (Figure 1). Water use and water availability are computed for over 4000 river basins covering nearly the entire terrestrial surface of the world (Alcamo *et al.* 1997; Döll *et al.* 1999). The Water Use model takes into account basic socio-economic factors that lead to domestic, industrial and agricultural water use, while the Water Availability model incorporates physical and climate factors that lead to river runoff and groundwater recharge (Figure 1). In the following sections we describe Version 2.0 of the WaterGAP model.

A first version of the model (WaterGAP 1.0 - Alcamo *et al.* 1997; Döll *et al.* 1999) was based partly on Klepper and van Drecht (1998). An entirely new version of the model (WaterGAP 2.0) has been used for the calculations in this report, and is described in the following sections.

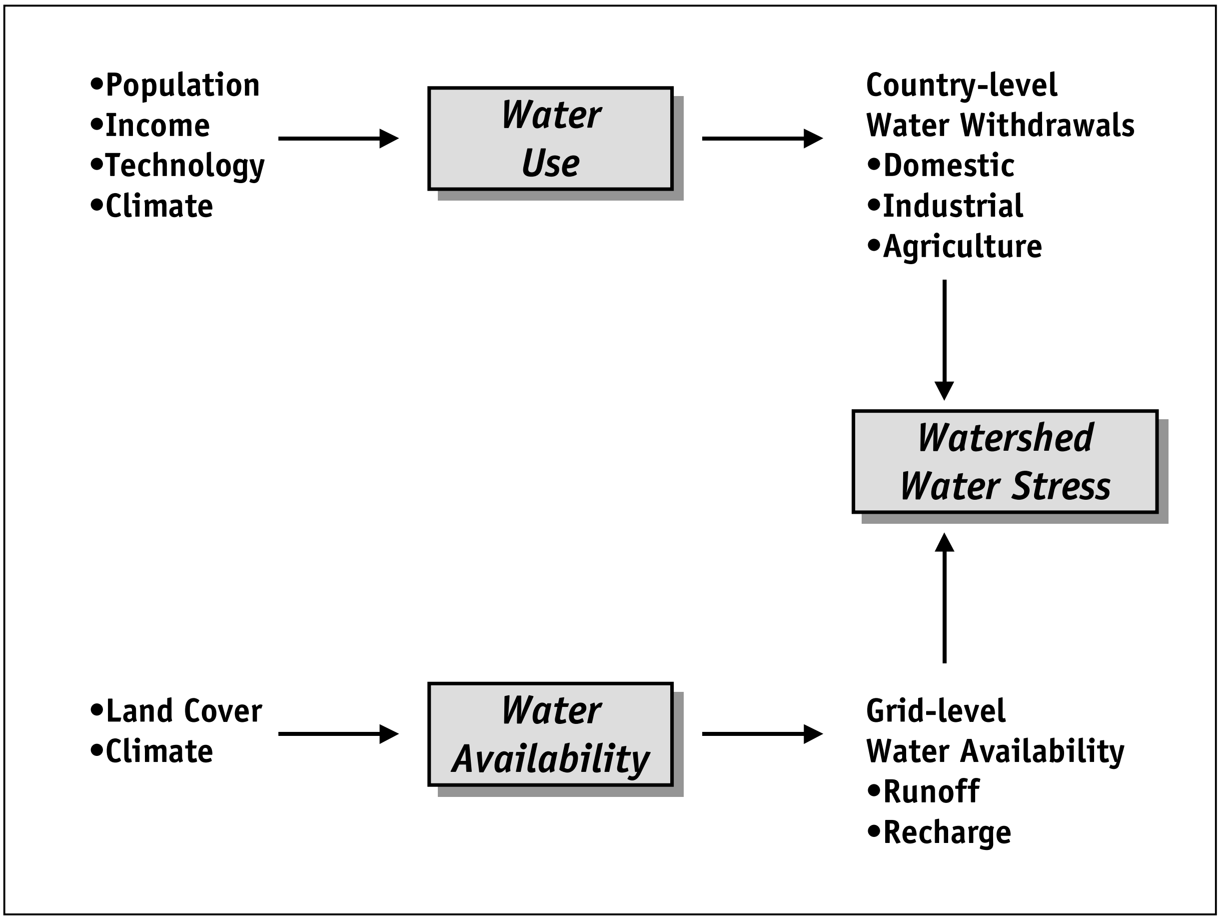

Figure 1. Block diagram of the WaterGAP model.

2.1 The Water Availability Model of WaterGAP 2.0 [2]

2.1.1 Introduction

For the scenario analysis in this paper it is necessary to estimate the *average availability* of water in each river basin in the world. We define water "availability" as fast surface runoff plus groundwater recharge, and "average" as the annual average during the so-called "climate normal" period of 1961 to 1990. Different approaches can be used to obtain the annual average availability. One approach is to sum and interpolate or extrapolate measured runoff data. A drawback to this approach is that reliable runoff values are only available in global databases for about 50% of the terrestrial surface of the earth (not including Antarctica and Greenland), and very few river basins have data from the entire climate normal period. An alternative approach is adopted in this paper, namely, to use the WaterGAP model as a tool for estimating current long-term runoff. The obvious disadvantage of this approach is that WaterGAP is inherently uncertain (as are all models). The advantage is that the model provides a consistent basis for calculating runoff in river basins that do not have runoff measurements. In addition, the model can be calibrated to existing long-term runoff data[3], even if these data cover only part of the climate normal period. The calibrated model can then be used to compute the climate normal average for every river basin. Hence with WaterGAP 2.0 we can consistently compute the water availability covering an identical averaging period for every river basin in the world.

2.1.2 Overview of Hydrologic Calculations

WaterGAP computes water availability on a grid and watershed-scale that is consistent with available global data. The model calculates the daily soil water balance of each grid cell, taking into account physical characteristics of watersheds such as soil, vegetation, slope and aquifer type. Calculations are detailed enough to be tested and calibrated to observed runoff data. The effect of changing land cover on runoff is taken into account via its effect on root depth and albedo. The effect of changing climate on runoff is taken into account via the effect of temperature, precipitation, and radiation on the vertical water balance. This balance consists of two main components,

- a canopy water balance (representing interception) which determines which part of the precipitation already evapotranspirates from the canopy, and which part reaches the soil, and
- a soil water balance which partitions the incoming precipitation into actual evapotranspiration and total runoff. The total runoff from the land area is then divided into fast surface runoff and groundwater recharge.

In addition, the water balance of open water bodies (lakes and wetlands) is computed.

2.1.3 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 2.0 by computing the balance of the water stored by the canopy as a function of the total precipitation, the throughfall and the canopy evapotranspiration. The evapotranspiration is computed as a function of leaf area index and other variables following Deardorff (1978). Daily val-

[2] This text was derived from Döll, P., Kaspar, F., Lehner, B. 2000. The hydrologic calculations of WaterGAP 2.0. Report of the Center for Environmental Systems Research, University of Kassel, Germany. Forthcoming.

[3] To within a 1% agreement between model and measurement.

ues of the leaf area index are modeled as a function of land cover and climate. No difference is made between the interception of rain or snow.

2.1.4 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 (S_s) and the total available soil water capacity (S_{smax}). The smaller the potential evapotranspiration from the soil, the smaller is the critical value of S_s / S_{smax} above which actual evapotranspiration equals potential evapotranspiration. S_{smax} is computed as the product of the total available water capacity in the uppermost meter of soil (Batjes, 1996) and the land cover specific rooting depth.

Total runoff is computed as a function of effective precipitation, S_s, S_{smax}, and a calibrated runoff factor, following the approach of Bergström (1994). The total runoff is then partitioned into fast surface and subsurface runoff and slow groundwater runoff (or base flow) based on rules that take into account cell-specific slope characteristics, soil texture, hydrogeology and the occurrence of permafrost and glaciers.

2.1.5 Lateral Transport

Within each grid cell, the runoff produced within the cell and the volume of water coming from the cell upstream is transported through a series of storages representing the groundwater, lakes, reservoirs, wetlands and the river. Then, the total cell discharge is routed along the drainage direction map to the next downstream cell. This map describes the estimated gravitational flow routing between approximately 67,000 grid cells and is based on various digital and analog continental drainage maps. The cells are connected to each other by their respective drainage direction and are thus organized into drainage basins. Each cell can drain only into one of the eight neighboring cells.

2.1.6 Calibration and Regionalization

The hydrological model was calibrated against long-term average annual discharges, measured at 309 stations, by adjusting the runoff coefficient γ. The runoff coefficient is assumed to be the same in all the upstream cells of a station. Time series of monthly measured discharges were provided by the GRDC (1999). The time series did not exactly cover the period 1961-1990, but varying periods of very different lengths. For calibration, the average measured runoff during last thirty measurement years was taken into account (or fewer years, depending on data availability).

After calibration, modeled and measured discharge at the outlet of these basins did not differ by more than 1% during the calibration period. In 206 out of the 309 basins, this agreement was achieved by only adjusting the runoff coefficient. For the other 103 basins, an additional correction factor was introduced. The basins cover most of the world's densely populated regions and 45% of the global land area (except Antarctica and Greenland).

A procedure was then needed to estimate the runoff coefficients of the remaining uncalibrated river basins in the world. Runoff coefficients here were estimated by correlating the runoff coefficients from the best-calibrated 206 basins with four parameters from these basins: 1) the 1961-1990 average values of potential evapotranspiration as a ratio of the total precipitation, 2) 1961-1990 average temperature, 3) the area of open freshwater (with wetlands at their maximum extent) as a ratio of the total catchment area and 4) the groundwater recharge factor (groundwater recharge as a ratio of total runoff from the land surface). This correlation was then used to set the runoff coefficients in the uncalibrated basins. Thus, for modeling the long-term average water availability 1961-1990, calibrated runoff coefficients were used for 45% of the global land area, and correlated runoff coefficients for the rest.

2.1.7 Validation and Comparison of Calculations

For validation the computed long -term annual average water availability is compared to literature estimates or measured discharges. This is done for river basins (Table 1), countries (Table 2), and continents (not shown).

The results for river basins must be judged differently for the following cases:

1. For some river basins the hydrological model of WaterGAP 2.0 was calibrated against the discharge at a measurement station.
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.
3. In still other river basins, no calibration was possible.

Table 1 - Comparison of computed and observed long-term average river discharges in selected river basins, in cubic-kilometers per year

River	Station	WaterGAP 2.0 [a] (computed)	GRDC [b]	Probst and 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 2 - Comparison of estimated long-term average runoff (internal renewable water re-sources) of selected countries, in km^3/a.

Country	WaterGAP 2.0 [a]	World Resources Institute (1998) [b]	Shiklomanov (1999) [c]	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 [d]
United States	1984	2459	2900	1928 [e]

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

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 calculations in Table 1 (marked with an *f* superscript) show the close agreement of model and measurements in this case. Also, using results from the Yangste River as an example, Figure 2 shows that the model agrees fairly well with annual flows even though up to now it has only been only calibrated to long-term average flows.

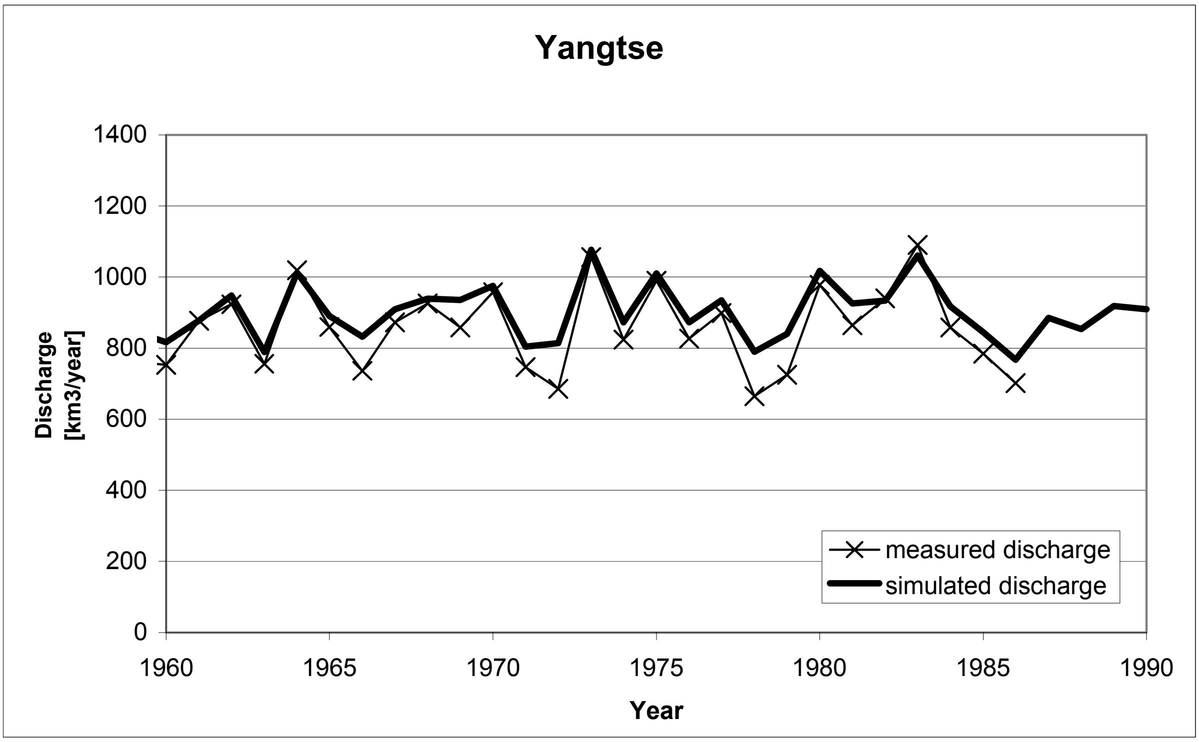

Figure 2. Comparison of computed and measured runoff of the Yangste River.

In Case 2 (calculations marked with a *d* superscript in Table 1) discrepancies might be much higher because – as is well known – calibration parameters are scale- and domain-dependent. Case 3 (calculations marked with an *e* superscript in Table 1) is the most difficult test for the model, as discharge is computed without any basin-specific information on actual discharge.

Table 2 demonstrates the large difference between various estimates of runoff in countries. In the case of countries, the differences could be due to different allocations of the discharge of boundary rivers to countries. The uncertainty of the runoff computed by WaterGAP is deemed to be of the same degree as that of other estimates.

2.2 The Water Use Model of WaterGAP 2.0

Water use in the WaterGAP 2.0 model is first computed for each country and then allocated to grid cells and river basins. We divide water use on a country level into three sectors: agriculture, domestic and industrial. We further sub-divide the agriculture sector into livestock and irrigation components. A similar subdivision is not possible at this time for the domestic and industry sectors because of the lack of data from most countries.

Water use in the current version of WaterGAP is equivalent to water withdrawal. Part of the withdrawn water becomes return flow and may be reused by other water users. We compute water withdrawals rather than water consumption because (i) the quality of return water can be very poor, and therefore may hinder its re-use, (ii) the locations of water users within a river basin are unknown. If they are clustered together then withdrawals will give a better indication of a local depletion of water resources than consumption. (iii) More global data are currently available for withdrawals than for consumption.

2.2.1 Key Concepts – Structural Change and Technological Change

Two main concepts are used for modeling water use – “structural change” and “technological change”. These concepts are borrowed from research on long term trends of technology and energy (see, e.g. Grübler 1998.). We use them here because they provide a transparent, long-term and consistent view of human behavior with regards to water use. Moreover, a water use model based on these concepts does not require extensive data, which is an important consideration given the lack of data from most countries.

The basic idea of “structural change” of water use is that the per unit water use (water use per capita or per economic unit) changes with the development of economies and lifestyles. Here we call per unit water use “water intensity”[4]. This concept makes the common sense assumption that the average person in poorer countries, where indoor plumbing is rare, uses far less water than in richer countries where modern water appliances are used. As a result, domestic water use per person is also smaller. According to the concept of structural change, water intensity increases with income as households acquire more water-consuming appliances (Figure 3).

[4] In WaterGAP2.0, the units of water intensity in the domestic sector are annual water withdrawals per capita, in the industrial sector annual water withdrawals per unit national energy production, and in agriculture mm (volume of water withdrawn per year per irrigated crop area).

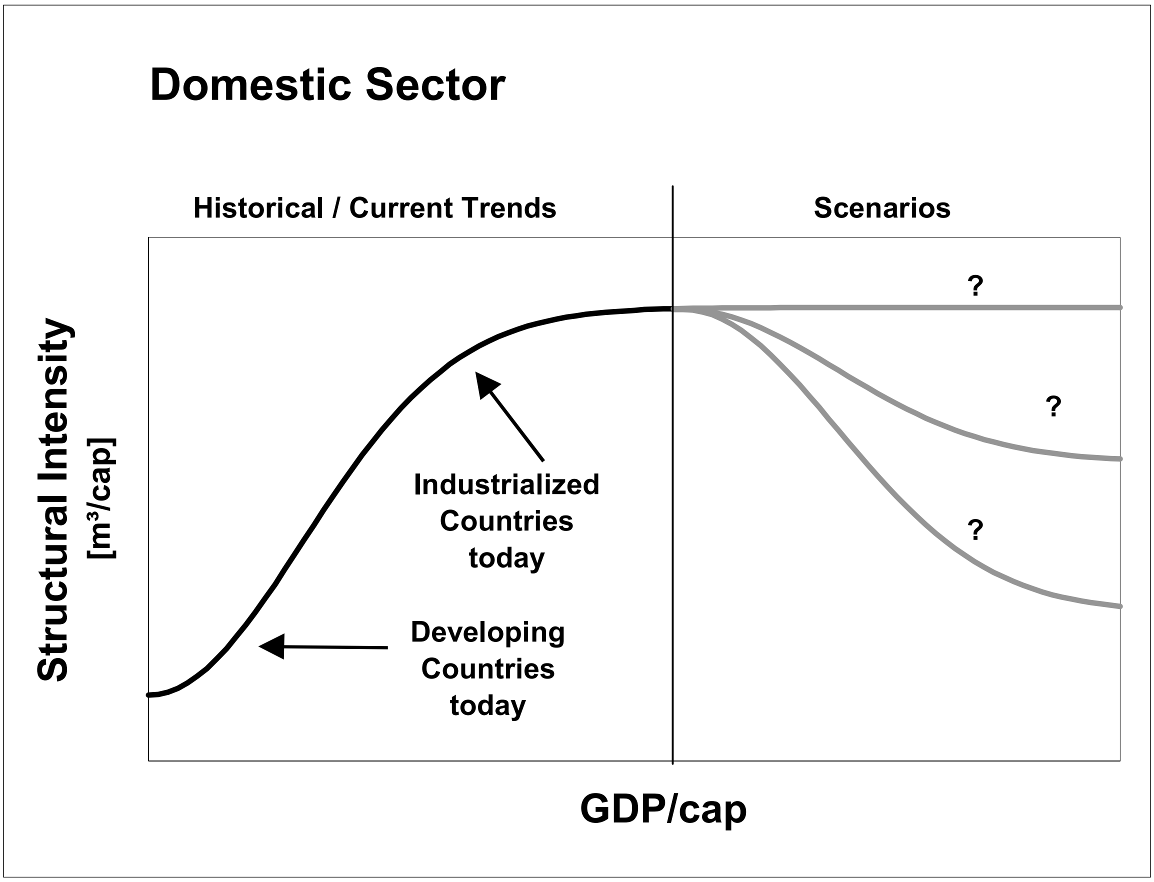

Figure 3 (a). Conceptual model of structural change in the domestic sector.

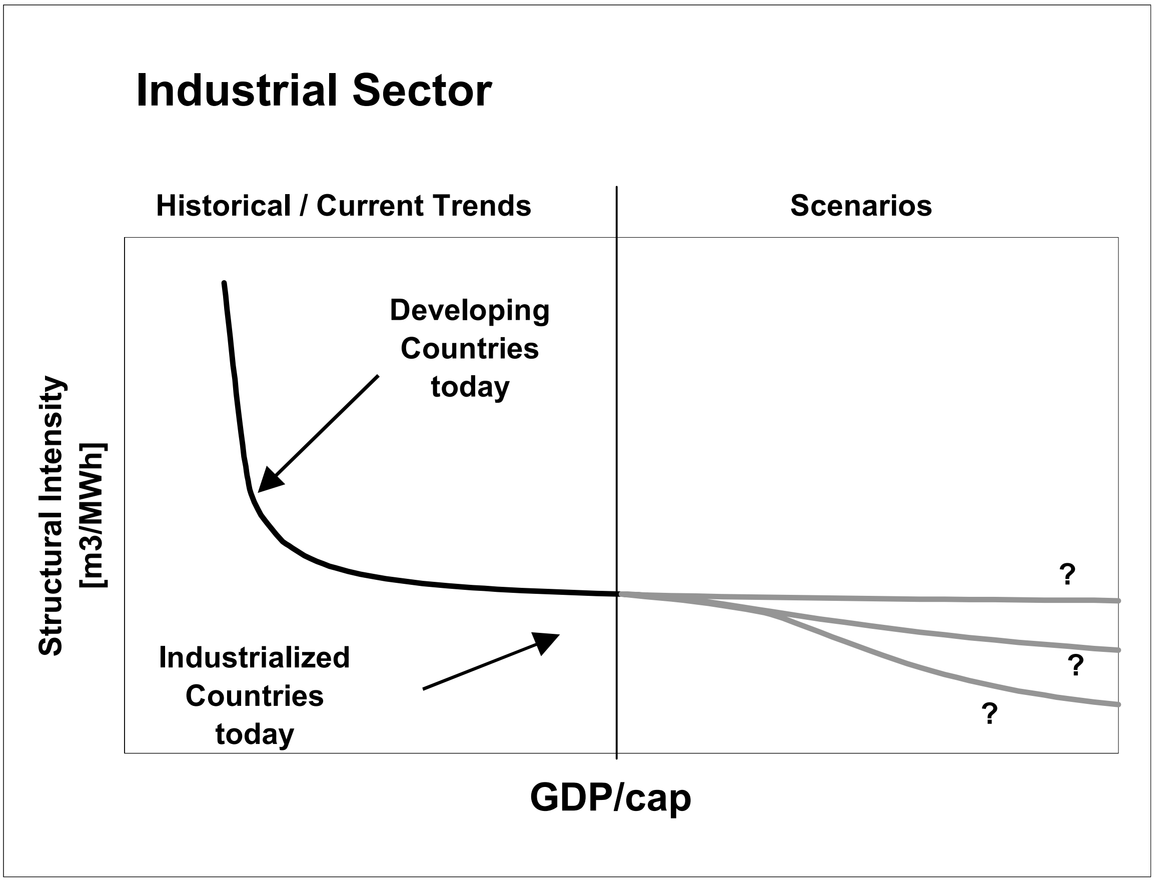

Figure 3 (b). Conceptual model of structural change in the industrial sector.

Finally a point is reached where the average household is saturated with dishwashers, washing machines, and other appliances, and water intensity then stabilizes or decreases [5]. This change in the mix of water-using methods with income is called "structural change" of water use, and it is represented by a sigmoid curve in the WaterGAP model (Figure 3).

In the industrial sector, historical data derived from Shiklomanov (1997) show a sharply decreasing intensity with income for poorer regions and a leveling off after middle income is reached (Figure 3). In richer regions the structural water intensity has either stabilized or has a very slight downward trend. Intensities are high in poorer regions because the small amount of industrial water use (comprising both water needed for electricity generation as well as water used in the manufacturing sector) is divided by an even smaller amount of generated electricity to obtain very large intensities in units of m^3 per MWh. As a country develops, the electricity sector dominate the industrial water use sector and a stable water intensity is normally reached which reflects the mix of thermal and non-thermal power plants that make up the electrical sector (Figure 3). The structural water intensity is higher where thermal plants dominate electricity production. For example, the structural water intensity in Germany (where thermal plants predominate) is 59 m^3 per MWh in 1995, as compared to 11 m^3 per MWh in Norway (where most electricity is generated by hydroelectric plants).

Structural changes can also have a decisive influence on the amount of water needed for agriculture. One example is the global shift to greater consumption of meat which increases the demand for irrigated land to grow feed for livestock. Another type of structural change is the possible shift from more intensive irrigated agriculture to more intensive rainfed agriculture, or vice versa.

While structural changes can either increase or decrease water intensity with income, "technological changes" has usually led to improvements in the efficiency of water use and a decline in water intensity over time. 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 industrial sector, technological changes were the likely cause of the 2.2 % per year drop in water intensity in the U.S. manufacturing sector between the 1950s and 1980s (Carr *et al.,* 1990). Between 1975 and 1995, the water intensity of Germany's industrial sector showed a decrease of 1.9 % per year (German Federal Statistical Agency, 1996) attributed mostly to efficiency improvements.

In the WaterGAP 2.0 model, structural changes proceed parallel to technological changes, and they combine to give changes in the resulting water intensities shown in Figure 4b and Figure 5b.

[5] The structural water intensity is computed from historical estimates of water intensity by assuming a specific historical rate of improvement in water efficiency, and then subtracting the assumed rate of improvement from the historical data. In effect, we pose the question, what would the water intensity have been if there had been no efficiency improvements? If an efficiency improvement greater than zero is assumed, then the structural water intensity will be somewhat larger than the historical water intensity.

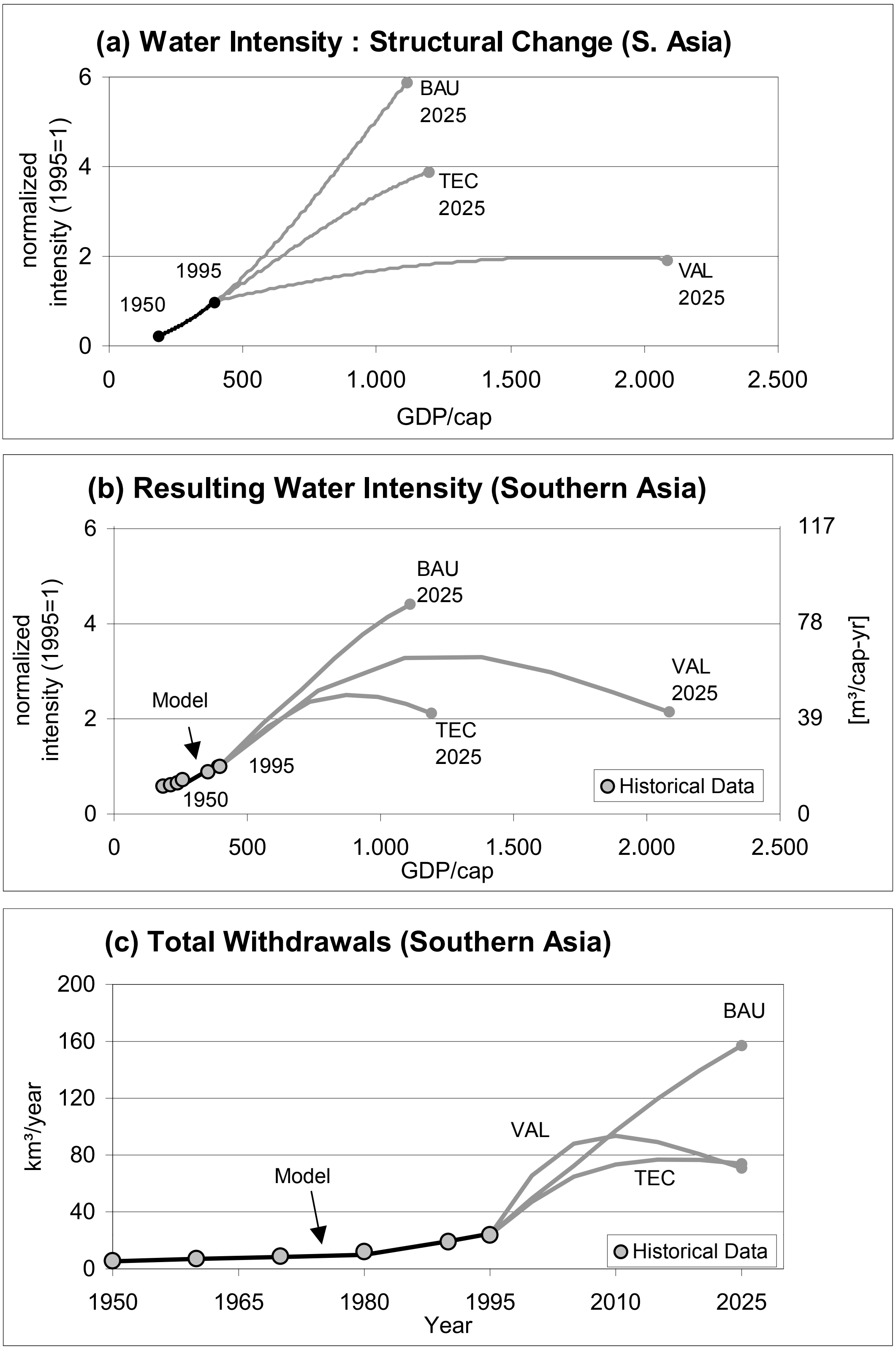

Figure 4. Domestic Water use calculations for Southern Asia (India, Pakistan, Bangladesh, Bhutan, Nepal, Sri Lanka, and the Maldives), based on regional aggregation in Shiklomanov (1997).

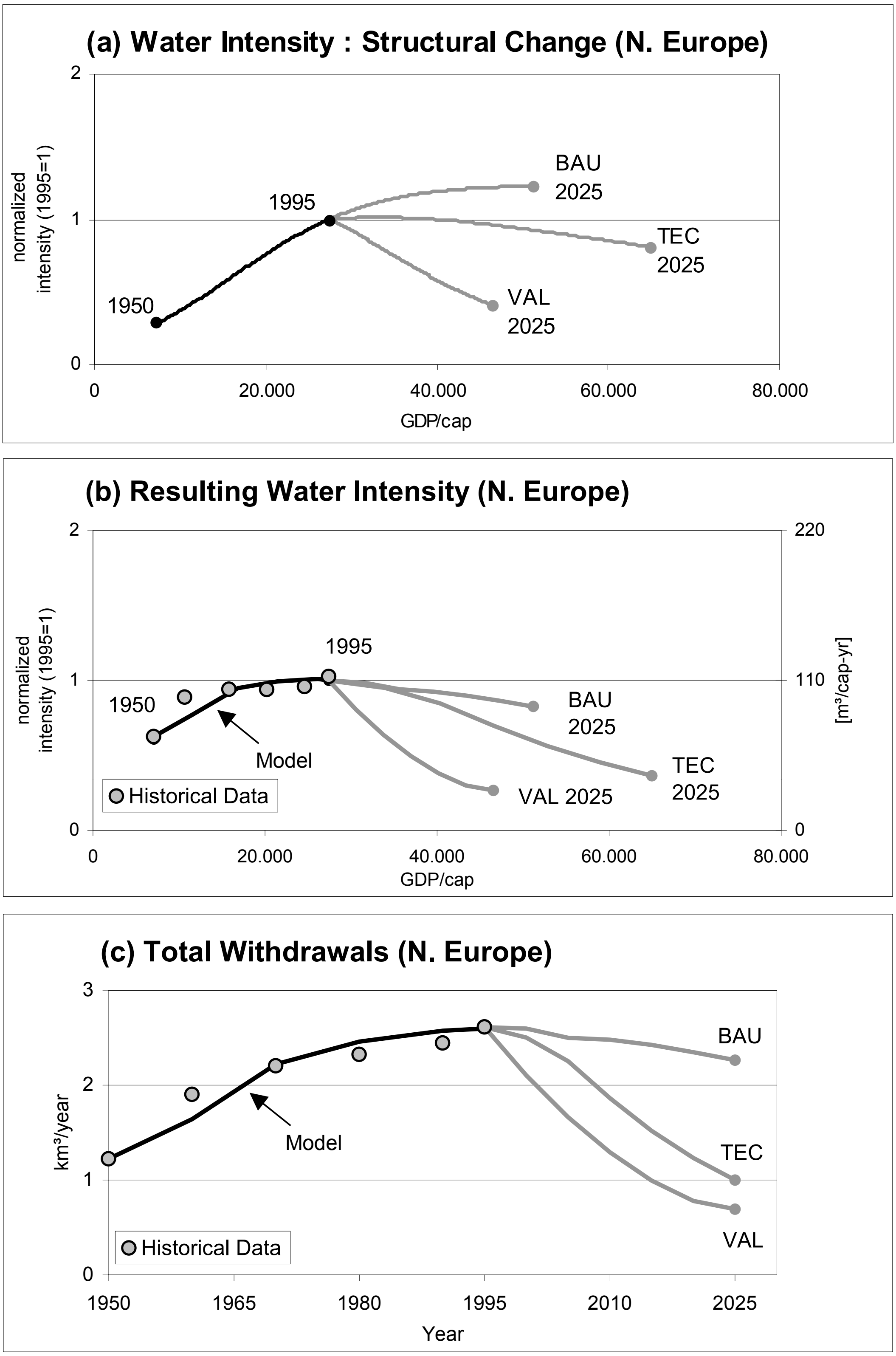

Figure 5. Domestic water use calculations for Northern Europe (Nordic countries), based on regional aggregation in Shiklomanov (1997).

2.2.2 Computing Water Use in the Domestic and Industry Sectors

Water use in the domestic sector is computed on the country-level using the following procedure:

1. For each of 26 regions we use historical data from Shiklomanov (1997) to derive a curve for structural water intensity as shown in Figure 4 and Figure 5.[6] We also take 1995 base year country data from Shiklomanov (1997). (Note, the structural water intensity is a derived, not an observed, quantity. But, the resulting water intensity, which is computed from structural change and technological change in Step 3, is an observed quantity).
2. We compute the future structural water intensity of a country based on the appropriate regional curve in Step 1, and based on a country's future GDP/cap (Figure 4a and Figure 5a).
3. We multiply the structural water intensity from Step 2 (changes due to structural change) by the assumed efficiency improvements (due to technological change) to obtain the resulting water intensity (Figure 4b and Figure 5b). A minimum water intensity is specified for both industrial and developing countries, as described in Appendix A.
4. The resulting water intensity is multiplied by the population of a country to obtain total domestic withdrawals for that country (Figure 4c and Figure 5c).
5. Country-level withdrawals are allocated to different grid cells within a country based on the population density and the ratio of rural to urban population of each grid cell, and the population with access to safe drinking water. 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.

Figure 4 and Figure 5 shows domestic water calculations for Southern Asia and Northern Europe. Note that the historical data for structural water intensity for Southern Asia (Figure 4a) corresponds to the steep part of the curve shown in Figure 3, while the data for Northern Europe (Figure 5a) corresponds to the flat part. This means that in Southern Asia structural water intensity (but not necessarily the resulting water intensity) will grow sharply for most scenarios when GDP/cap increases (Figure 4a), but in Northern Europe it will only slowly increase or perhaps decrease with growing income (Figure 5a). If we then take into account the effect of technological changes that improve water use efficiency with time, we obtain the water intensities shown in Figure 4b and Figure 5b. These water intensities are then multiplied by population to obtain the withdrawals shown in Figure 4c and Figure 5c.

Water use in the industrial sector is computed by a similar procedure. However the structural curves (Step 1) for industry have a hyperbolic rather than sigmoid form, as explained in Section 2.2.1. The resulting water intensity is obtained as for the domestic sector by multiplying the structural intensity by efficiency improvements with time. The resulting water intensities are then multiplied by the electricity use[7] in the country to obtain industrial water withdrawals. Country-level withdrawals are then allocated to grid cells according to the relative size of their urban population. This assumes that most industrial activity occurs in urban areas.

[6] To derive this curve we use data derived from Shiklomanov as explained in Footnote 5.

[7] Industrial water use consists primarily of two components – manufacturing and electricity generation. Unfortunately, it is not yet feasible to distinguish between these two components on the global level because of the lack of data from most countries. Hence, we select national electricity production as the driving force of industrial water use because electrical generation dominates industrial water use in most countries, and because the amount of electricity produced in a country gives a rough indication of the level of its manufacturing activity.

2.2.3 Water Use for Agriculture

2.2.3.1 Overview of Calculations

Agricultural water uses are divided into two categories – livestock and irrigation. In most parts of the globe, livestock water use is very small compared to irrigation water use. Consumptive use of water is assumed to be equal to withdrawals and is computed on a global grid of 0.5^0 x 0.5^0 by multiplying the number of livestock per grid cell by their use of water per head per year.

The irrigation model of WaterGAP 2.0 computes net and gross irrigation requirements, which reflect an optimal 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 evapotranspirated 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 ratio of net over gross irrigation requirement is called "irrigation water use efficiency".

The irrigation model uses a new digital global map of irrigated areas (Döll and Siebert, 1999a) as a starting point for simulations. The model simulates the cropping patterns, the growing seasons and the net and gross irrigation requirements, distinguishing two crop types, rice and other crops. Only rice is distinguished because data are available for the extent of irrigated rice areas (IRRI, 1988) but not for other irrigated crops.

The computation of the net and gross irrigation requirements is carried out in four steps.

1. Using a rule-based system, the cropping pattern for each cell with irrigated land is modeled. The model computes 1) whether only rice, only non-rice or both are irrigated and 2) whether, within one year, there are one or two growing seasons for rice and non-rice. We assume a growing period for both rice and non-rice of 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.

2. The optimal growing seasons are determined for each cell. The start date of each growing season is computed for each crop and growing season by ranking each 150-day period within a year according to optimal temperature and precipitation conditions, which depend on the growing stage of the crop. The planting date is then defined by the highest ranked growing period; in case of two consecutive growing periods, the combination with the highest total number of ranking points is chosen.

3. The net irrigation requirement of the rice and non-rice crop is computed for each day of the growing season as the difference between the crop-specific potential evapotranspiration and available precipitation. In this calculation the available precipitation is the fraction of the effective precipitation (as rainfall and snowmelt) that is available to the crop and does not run off. This approach is similar to the CROPWAT approach of Smith (1992). The net irrigation requirements are calculated by using a time series of climatic data. For calculations in this paper, we use the average requirement of the climate normal period (1961-1990).

4. The gross irrigation requirement (equivalent to “agricultural water withdrawals” in this paper) is calculated by taking into account regionally-varying irrigation field efficiencies rang-

ing from 0.35 in South and East Asia to 0.7 in Canada, North Africa and Oceania (Döll and Siebert, 1999b). These are rough estimates of project-level irrigation efficiencies[8].

2.2.3.2 Model Validation

As a test of the global irrigation model we compare computed cropping patterns, growing seasons and irrigation requirements with independent data. In most cases, model calculations come close to reality. For example, the estimated net irrigation requirement in Germany ranges from 80 to 110 mm/yr (Roth, 1993). By comparison, WaterGAP computes 72 mm/yr for a cell in Northern Germany and an average of 112 mm/yr for the whole country. The best independent irrigation water use estimates are available for the USA (data per county for 1995, Solley et al., 1998). The good correspondence of the USA values with our model results is confirmed by a state by state comparison of modeled and independent irrigation requirements, which is characterized by a correlation coefficient of 0.975. However, the actual rice production in California is not simulated by the model. There are other cases requiring an improvement in the performance of the model -- For example, the model estimates that crops in Spain are only irrigated during the summer, when in reality crops are also partly irrigated during the winter.

For further information about the agricultural water use model, the reader is referred to Döll and Siebert (1999b).

2.2.3.3 Application to the World Water Scenarios

In order to calculate irrigation water use for the scenarios presented in this paper, we first compute the future extent of irrigated area based on the country-scale scenarios for 2025 of IMWI (1999). These country-scale changes are allocated to current (1995) irrigation grid cells by assuming that each grid cell receives an identical amount of new irrigated area up to a maximum coverage of 90%. The irrigation requirements in 2025 are then computed for the new irrigated areas, subtracting water savings due to improved irrigation water use efficiencies. The impact of climate change is not taken into account in these scenarios, although it will be included in further analyses.

2.3 Assessment of WaterGAP Model Uncertainty

The global assessment of water resources as presented in this paper has unavoidable uncertainties due to errors or gaps in current data, because of the scale of approximations, and because any model used for projections is inherently uncertain. Although these uncertainties are unavoidable, it is still important to be as explicit as possible about them in order to ensure the proper use of results in this paper. It is also important to rank the importance of different kinds of uncertainties so that research can be focused on reducing these uncertainties in future calculations. With this mind, Figure 6 presents a preliminary and qualitative assessment of the uncertainties of the model and scenarios in this paper.

---

[8] As part of the scenario analysis for the World Commission on Water for the 21st Century, it was agreed that the data of Shiklomanov (1997) would be used as reference data for country-level water use in 1995. Therefore, for the purposes of this paper, we have multiplied the WaterGAP 2.0 calculations of gross irrigation requirement for 1995 by an "adjustment factor" so that these values agree exactly with the estimates of Shiklomanov (1997). This factor is only used for calculations in this paper.

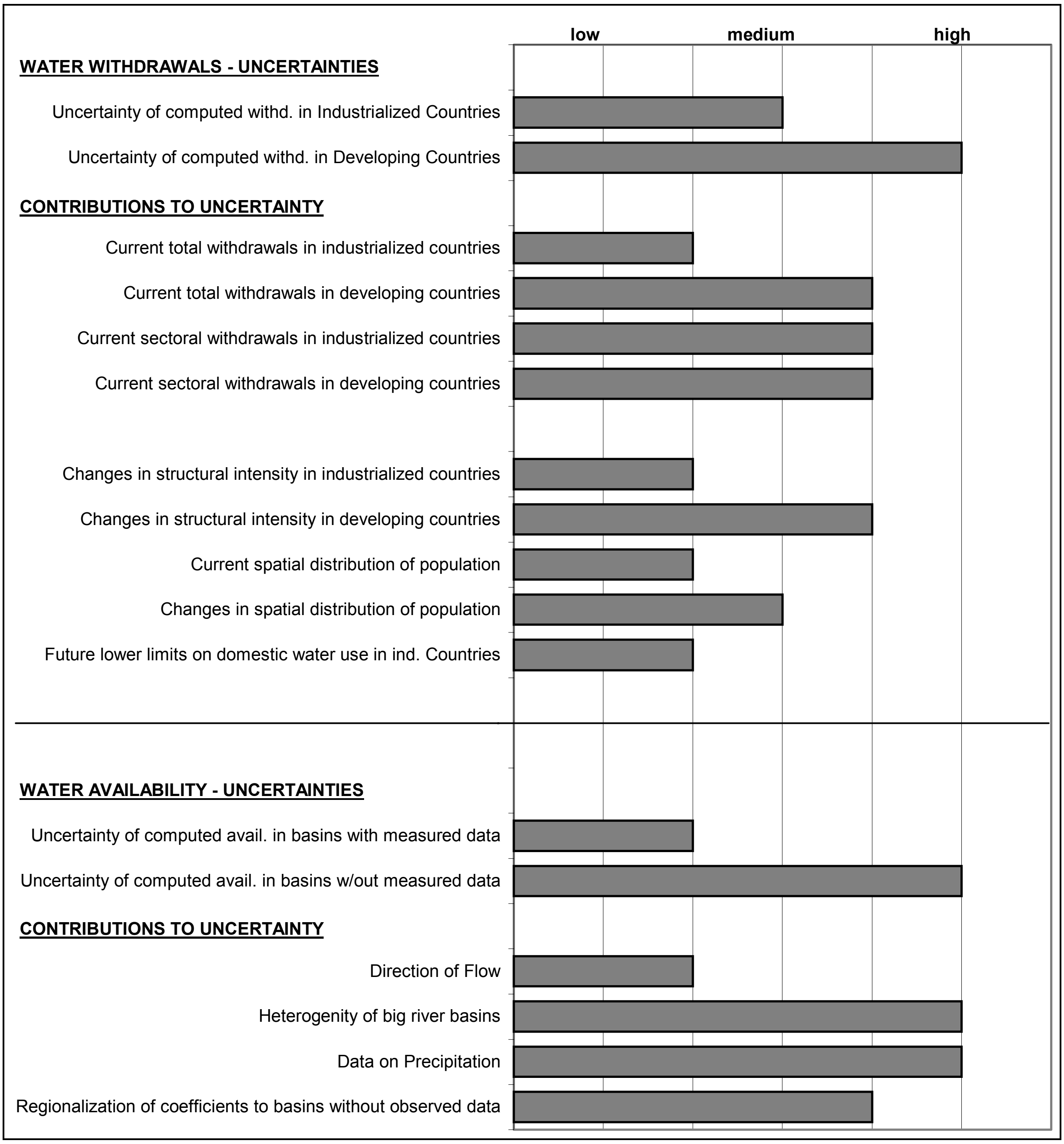

Figure 6. Qualitative assessment of uncertainties in model and scenarios.

2.3.1 Uncertainty of Future Water Withdrawals

We estimate that the future trends of total withdrawals from industrialized countries have a lower uncertainty than for developing countries for two main reasons: First, estimates of current total withdrawals of industrialized countries have lower uncertainty (although estimates of withdrawals for specific sectors are unreliable for both industrialized and developing countries.) Second, the trends in structural water intensity in the domestic and industry sectors are already stabilizing in industrialized countries, but not in developing countries (see Figure 4 and Figure 5, for example). Hence the near-term trend of structural water intensity is clearer for industrialized countries than for developing countries.

An additional, but probably less important, source of uncertainty is the allocation of country withdrawals to river basins based on the spatial distribution of population within the river basin (and other factors). The uncertainty of the future distribution of population adds uncertainty to the future estimate of river basin withdrawals.

For estimates in industrialized countries another source of uncertainty is the assumed lower limits on domestic water use.

2.3.2 Uncertainty of Current Water Availability

For water availability, the level of uncertainty is larger in river basins without measured runoff data. As explained in Section 2.1, the model can be calibrated to runoff data and then be used to compute a fairly accurate estimate of the "climate-normal" water availability. But in basins without runoff data, the model must use coefficients derived from other river basins, and estimates of water availability will be more uncertain.

Two other sources of uncertainty in calculating water availability are (i) the estimation of precipitation within basins and (ii) the uncertainty of the direction of flow within a basin. Furthermore, additional uncertainty may arise in large river basins where run-off data are only available for parts of the basin. When these incomplete run-off data are used to calibrate model coefficients, the resulting coefficients may not be representative of the entire river basin. Hence, these coefficients might introduce further uncertainty when they are used to compute the entire basin's water availability.

3. Present Water Situation

Before examining scenario results, we first highlight the current water situation in the world as estimated by the model.

The top map in Figure 7 presents the water withdrawals in different river basins, the bottom map the water availability (sum of annual runoff plus shallow groundwater recharge). These calculations are representative of 1995 conditions, assuming that climate conditions in 1995 were close to climate normal conditions[9]. Data in both maps are given in mm/year so that the maps can be visually compared. Note that the highest density of water use occurs as expected in the high population areas of Japan, Coastal China, India, Pakistan, Central Europe, and the east and west coasts of North America. In the water availability map, the rainy parts of the world clearly stand out. Also, a visual comparison of both maps shows that in some areas, such as Southern Asia and in the Aral Sea Basin, water availability is relatively low and withdrawals are relatively high, indicating potentially high stress on water resources.

3.1 A Measure of Water Scarcity

To compare the level of water scarcity in different river basins we need a measure that incorporates the data in Figure 7. One transparent measure is the "criticality ratio" (CR) which is the ratio of average annual water withdrawals to water availability. The higher the criticality ratio, the more stress placed on available water resources by water use. In principle, the higher the value of CR, the more intensively the waters in a river basin are used, and the lower the water quality for downstream users. Hence, at high values of CR, the usage of water by downstream users can be impaired. Also, the higher the CR, the greater the chance of absolute water shortages during low flow periods.

At this time, there is no objective basis for selecting a threshold of CR between low and high stress. However, such thresholds are needed for global and regional assessments of water resources and therefore they should be given attention by researchers. In the meantime, for this paper we use the commonly used set of thresholds shown at the bottom of Figure 8 (see, for example, Raskin, 1997). In this scheme, criticality ratios between 0.4 and 0.8 indicate "high water stress", and greater than 0.8 "very high water stress". One can argue that the risk of absolute water shortages during low flow periods will be especially high if the *average* annual CR value is at or above 0.4.[10]

[9] "Climate normal conditions" refer to the average of the "climate normal" period of 1961 to 1990.

[10] Although the criticality ratio is based on average withdrawals and availability, it could also indicate when the risk of water shortages during low flow periods is high. If we assume that in a one-in-ten-year dry year the annual runoff is between 0.3 to 0.7 times the climate normal runoff, and further assume that consumption is on the average 60% of withdrawals (Shiklomanov, 1999), then a CR = 0.4 is equivalent to a consumption to availability ratio of 0.34 in river basins with low variability, and 0.8 with high variability. Hence, once every ten years, basins with average CR = 0.4 should theoretically consume between 34 and 80% of their total available runoff (here we neglect groundwater use which would increase water availability, but not indefinitely). Basins with higher values of CR would consume an even greater percentage of their total available runoff. Depending on how withdrawals are spatially distributed within a basin, a CR ≥ 0.4 could therefore lead to absolute shortages along some stretches of a river during parts of the year, and the low remaining flows could be insufficient to sustain aquatic ecosystems. Storage of runoff in reservoirs can provide some security against shortages, but in developing countries only a small percentage of a river basin´s runoff is normally stored.

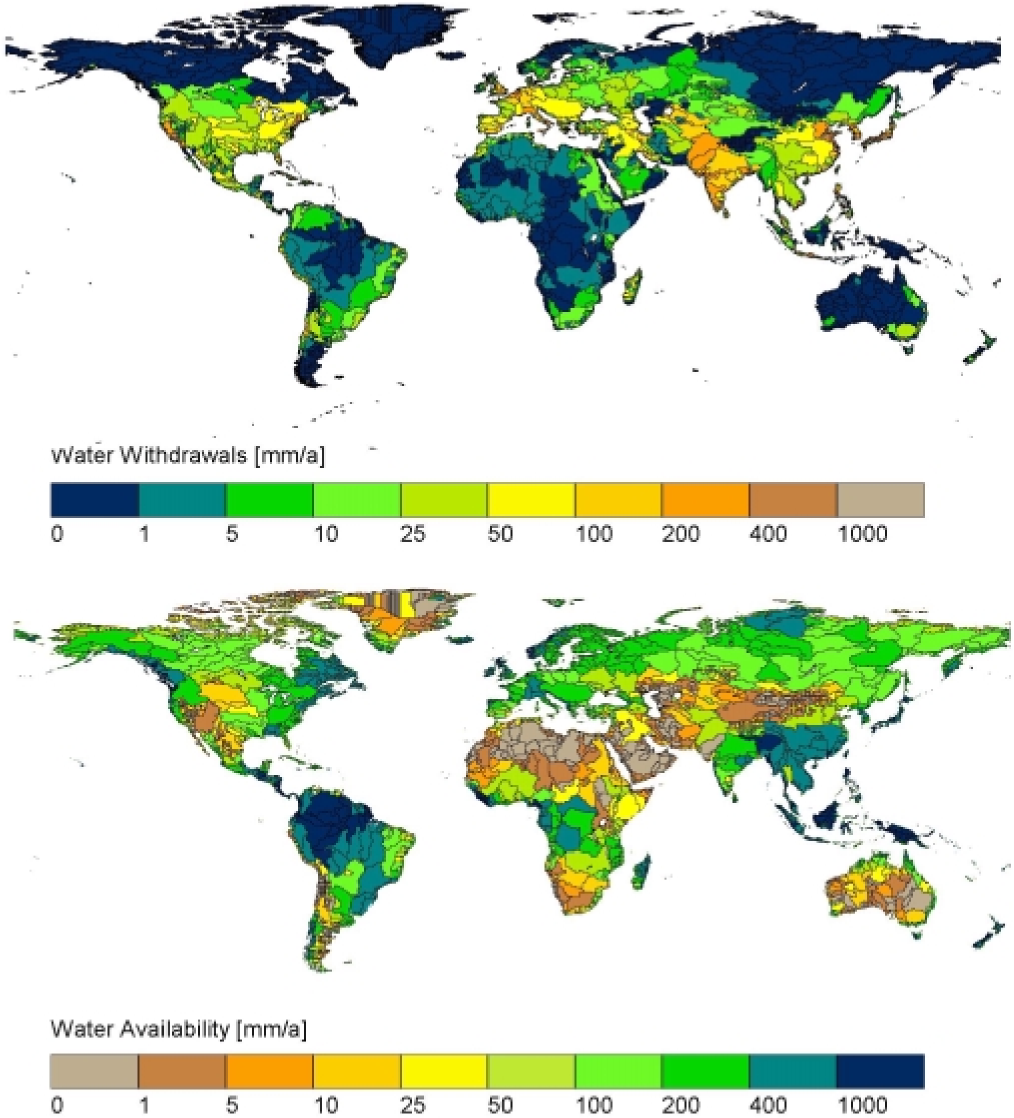

Figure 7. The world today (1995): Withdrawals (top map), Water availability (bottom map).

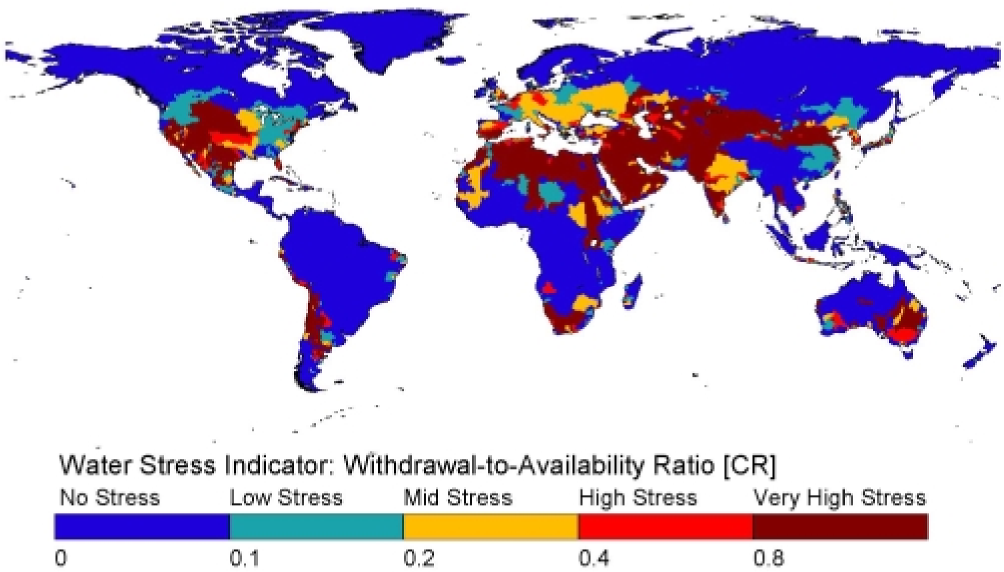

Figure 8. The world today (1995): Water Stress (note that the 'high stress' and 'very high stress' categories are labelled as 'severe stress' category when referred to jointly).

Assuming for now that CR > 0.4 indicates severe water stress (this comprises the high and very high water stress categories), will the effects of this severe water stress be the same on all countries? The answer is, probably not. In industrialized countries water is commonly purified before it is returned to a river and passed on to other users. This implies that the same water resource can be used many times before its quality becomes too poor for further use. Also, many river basins have reservoirs that store water from high runoff periods to make this runoff available during drier periods. Moreover, industries in these countries tend to recycle their water supply fairly intensively, which also enables intensive use of the water resource, without frequent water crises.

By contrast, most developing countries do not treat wastewater, and a smaller proportion of total runoff is stored in reservoirs and distributed during dry periods. Also, industries do not intensively recycle their water supplies. This means that intensive use of water can lead to the rapid degradation of water quality for downstream users, and absolute shortages during droughts. The consequence can be on-going and frequent water emergencies.

Although the assumed threshold of severe water stress is very uncertain, we later show by a sensitivity analysis that conclusions based on this value are fairly robust.

3.2 Stress on Water Resources

Figure 8 shows the criticality ratio for 1995. As expected, most of the world's desert areas are in the severe water stress category (i.e. CR > 0.4). Also in the high or very high stress categories are some of the large basins of China (including the Yellow River), the Krishna in India, much of Central Asia, coastal areas in Latin America, parts of Europe, and much of the Western United States. The percentage of area in the severe water stress category varies from 5% (Central Africa) to 88% (Middle East) (Table 4). Globally, 25% if the earth's terrestrial surface (excluding Greenland and the Antarctica) is under severe water stress. Approximately 2.1 billion people live in river basins where the stress on water resources is severe, and nearly half of these people live in Southern Asia and China (Table 5).

4. A Reference Scenario: "Business-as-usual" (BAU)

4.1 Assumptions

The Business-as-usual (BAU) scenario examines the consequences of continuing current trends in population, economy, technology and human behavior up to 2025 (summarized in Table 3).

Table 3 - Basic assumptions of different scenarios – Developments until 2025.

	Business-as-usual (BAU)	*Technology, Economics, and the Private Sector (TEC)*	*Values and Lifestyle (VAL)*
General			
Global Population	8.0 billion	7.9 billion	7.5 billion
Annual National Per Capita Income (annual increase, varies by region)	Ranges from 1.0% (Japan) to 4.2% (China)	Same as BAU until 2005, thereafter - ranges from 1.1% (Central America) to 4.1% (North Africa)	Same as BAU until 2005, thereafter - ranges from 0.1% (Japan) to 7.7% (China)
Domestic Water Use			
Water intensity (m^3/cap-yr)	Increases and then stabilizes with increasing incomes	Decreases by *one-third* compared to BAU at same national income	Decreases by *two-thirds* compared to BAU at same national income
Water use efficiency (% annual increase)	2% until 2005 1% thereafter	2% until 2005 3% thereafter	2% until 2005 2% thereafter
Industrial Water Use			
Electricity production (% annual increase, varies by region)	Ranges from 0.8% (Japan, W. Europe) to 10% (East Africa)	Same as BAU until 2005, thereafter – ranges from 0.2% (North America) to 15% (East Africa)	Same as BAU until 2005, thereafter – ranges from -0.2% (Japan) to 15% (East Africa)
Structure	Mostly thermal plants, water-intensive industries	Many non-thermal plants, non water intensive indus.	Many non-thermal plants, non water intensive indus.
Water use efficiency (% annual increase)	2% until 2005 1% thereafter	2% until 2005 3% thereafter	2% until 2005 2% thereafter
Agricultural Water Use			
Irrigated Area:			
• Global change relative to 1995	+1.5%	+23%	+5%
• Change in different countries relative to 1995)	+ 6.8% (in Turkey, Brazil, and India only)	-24% (Saudi Arabia) to +122% (Brazil)	-100% (Saudi Arabia) to +56% (Benin/Burkina Faso)
Water use efficiency (% annual increase, varies by country)	Increases by 0.3%	Increases by up to 0.6% (only 0.3% in low income and transitional countries)	Increases by 0.9% (less in countries that are already efficient)

Under this scenario, global population is assumed to grow from about 6 to about 8 billion between 1995 and 2025. The population of industrialized regions is stable at below 1.0 billion, and grows rapidly to 7.0 billion in developing regions. Per capita national income grows at a rate from 1.0 to 4.2 % per year, depending on the region (Table 3). Structural change in the domestic sector tends to increase water use per capita as national income increases, but a maximum value is reached at high income (see Figure 3a). At the same time, technological changes continue to reduce water use per capita at its current pace (about 2 % per year) until 2005 when the pace is assumed to slow to 1 % per year. The combination of these two factors gives the net water use per capita in the domestic sector for each country.

Under the BAU scenario, the fraction and type of thermal power plants in the electricity sector remains the same as now, so structural change is not a factor in changing the water use per unit energy production. Nevertheless, the resulting water intensity declines because of continuing efforts in industry to improve water efficiency, although this happens at a slower pace after 2005. These and other assumptions of the domestic and industrial sectors are summarized in Table 3.

In the agriculture sector, the Business-as-Usual scenario (BAU) assumes a continuation of current trends in food policy.[11] The rate of investment in agricultural development drops off and this slows the rate of improvement of crop yields. Investment in irrigation falls off, and some irrigation area is lost to salinization and waterlogging – The net effect is that the extent of irrigated cropland stagnates in all but three countries[12], and the field efficiency of irrigation only slowly improves (Table 3). Under BAU, the global calorie availability per capita increases by 6 % between 1995 to 2025, and the estimated number of malnourished pre-school children declines from 160 million in 1995 to 114 million in 2025 (IFPRI, 1999).

4.2 Water Withdrawals

In industrialized countries[13], economic growth up to 2025 tends to increase domestic and industrial water use, but this is offset by increasing water use efficiency and the saturation of water demands in households and industry. Also, the extent of irrigated land stabilizes and water is used more efficiently on this land. As a result, total water withdrawals in all sectors decrease (Figure 9).

The situation is different in developing countries – An increase in income leads to greater household water use per capita which is multiplied by the increasing number of people in these countries. Meanwhile, economic growth leads to an expansion of electricity demand and industrial output, and this leads to a large increase in water demands for industry. Even though water is used more efficiently in households and industry, these efficiency improvements are overwhelmed by pressures leading to increased water use. The net result is a large increase in water withdrawals in the domestic and industrial sectors of the developing world (Figure 9).

[11] These assumptions are taken from IFPRI (1999) and IWMI (1999).
[12] Turkey, Brazil, and India
[13] "Industrialized" countries here are the "high" income countries listed in World Bank (1997), and "developing" countries are all remaining countries.

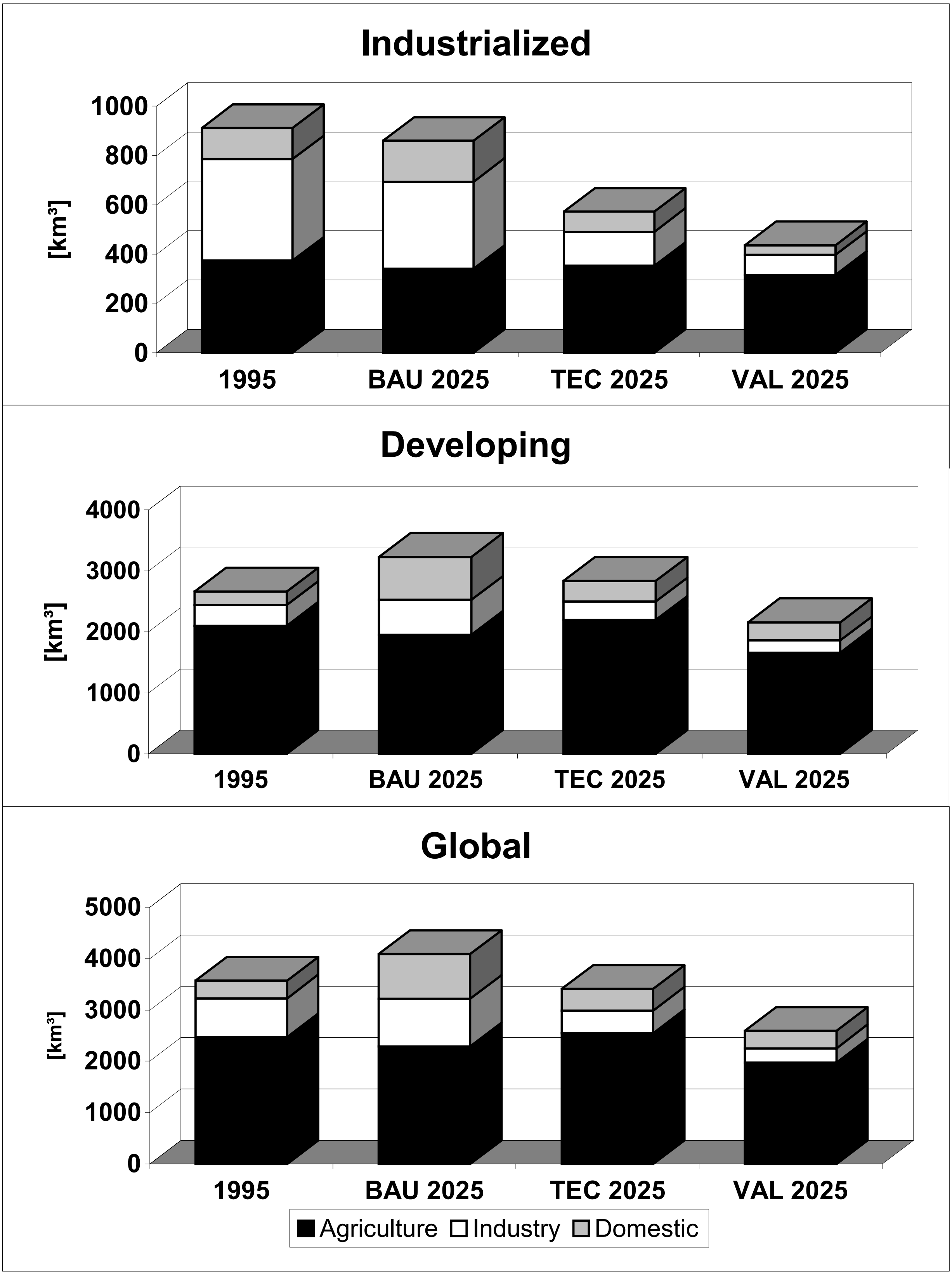

Figure 9. Water withdrawals: Industrialized and developing world, global sum.

Parallel to these developments, the extent of irrigated land in almost all developing countries stops growing (see discussion above), and crop production falls behind the demand for food. A spinoff effect is that the amount of water withdrawn for irrigation either stabilizes or slightly decreases (because of efficiency improvements) in most developing countries. Nevertheless, agriculture remains the major user of freshwater in the world, claiming 56 % of total global withdrawals (Appendix B).

The sum of trends in the domestic, industrial, and agricultural sectors add up to a significant net growth in total water withdrawals in developing countries between 1995 and 2025 (Figure 9). On the global level, the sum of trends in industrialized and developing countries under the Business-as-Usual scenario result in an increase in total water withdrawals from 3,572 km^3/year in 1995 to 4,091 km^3/year in 2025 (Figure 9 and Appendix B).

4.3 Stress on Water Resources

Because of an increase in water withdrawals, the pressure on water resources increases in over 60% of the total area of the world's river basins especially in large areas of Africa, Asia, and Latin America (Figure 10a). Consequently, the area of severe water stress (CR > 0.4) expands from 36.4 to 38.6 million km^2 between 1995 and 2025, and includes new areas on virtually all continents.[14] The increase is especially significant in Southern Africa, Western Africa, and South Asia (Figure 11 and Table 4). The change in area under severe water stress is not large in Africa and Latin America because here the increase in withdrawals occurs mostly in water-rich areas (Figure 11a). On these continents the problem may not be water shortages, but instead the need to rapidly expand water infrastructure to accommodate increasing water demands (See a further discussion of this in Section 6). Because of the new areas, but especially owing to population growth, the number of people living in areas where water resources are under severe stress increases from 2.1 billion in 1995 to 4.0 billion in 2025 (Table 5).

One question that arises is whether water scarcity could inhibit industrial development. Put another way, which water-scarce river basins also have large industrial water requirements? Figure 12 shows the river basins under severe water stress in which industrial water use makes up a large fraction (one-third or more) of total withdrawals. These areas include parts of the Korean Peninsula, large parts of Central Asia, some areas in Latin America, and parts of Europe and North America. In these river basins, especially in developing countries, industries will have to rigorously compete with household and agricultural water users for scarce water resources. Industries will either win this competition, or have to adapt to the situation by relocating to a river basin with more plentiful water, or by drastically reducing their water requirements.

Another important result of the BAU scenario is that 33% of the world's international shared river basins will be in the high or very high stress category in 2025 under the BAU scenario (Figure 13). These basins are also widely distributed on all continents. Here water users in the domestic, industrial and agricultural sectors from two or more countries will compete for the same

[14] For these calculations it was assumed that water availability in 2025 is the same as in 1995. This is not a particularly good assumption since climate and landcover change will probably modify runoff (see, e.g. Alcamo and Kaspar, 1998). But this was not taken into account in the Business-as-usual scenario because the Scenario Panel of the Commission felt that precipitation estimates from climate models were too uncertain to be included in this exercise.

scarce water resources. The competition for these water resources could be a source of tension between nations. More details about specific regions are given in Table 4, Table 5, and Section 6.

Table 4 – Area of regions and world (1000 km^2) with severe water stress (i.e. CR > 0.4). Percent of total area given in parentheses.

REGION	1995		BAU		TEC		VAL	
WORLD	**36407**	**(25%)**	**38649**	**(27%)**	**37708**	**(26%)**	**33901**	**(23%)**
North America	4310	(20%)	3827	(18%)	3575	(17%)	3448	(16%)
Central America	1057	(31%)	1044	(31%)	1209	(36%)	1036	(31%)
South America	1875	(10%)	1956	(11%)	1752	(09%)	1691	(09%)
Western Europe	1418	(18%)	1389	(18%)	1030	(13%)	774	(10%)
Eastern Europe	118	(08%)	118	(08%)	27	(02%)	13	(01%)
C.I.S.	1074	(06%)	1089	(06%)	605	(03%)	316	(02%)
Aral Sea Basin	2989	(74%)	3146	(78%)	2954	(73%)	2934	(73%)
Middle East	5431	(88%)	5676	(92%)	5317	(87%)	5298	(86%)
North Africa	6428	(67%)	6646	(69%)	7072	(74%)	6473	(68%)
East Africa	836	(18%)	927	(20%)	976	(21%)	973	(21%)
Western Africa	801	(16%)	1064	(21%)	1052	(20%)	1052	(20%)
Central Africa	288	(05%)	288	(05%)	288	(05%)	288	(05%)
Southern Africa	1161	(19%)	1638	(27%)	1588	(26%)	1161	(19%)
Australia	2020	(22%)	1834	(20%)	1918	(21%)	1738	(19%)
Japan (only)	96	(15%)	81	(13%)	38	(06%)	33	(05%)
China +	3793	(32%)	4171	(35%)	4656	(39%)	4009	(34%)
South Asia	2291	(49%)	3266	(70%)	3236	(69%)	2307	(49%)
Southeast Asia	422	(06%)	489	(07%)	413	(06%)	356	(05%)

Table 5 – Population (million people) living in areas with severe water stress (i.e. CR > 0.4). Percent of total population given in parentheses.

REGION	1995		BAU		TEC		VAL	
WORLD	**2138**	**(38%)**	**3993**	**(50%)**	**3524**	**(45%)**	**2627**	**(35%)**
North America	133	(44%)	161	(43%)	104	(28%)	83	(24%)
Central America	57	(37%)	104	(45%)	89	(39%)	82	(39%)
South America	52	(16%)	94	(21%)	73	(16%)	60	(15%)
Western Europe	176	(40%)	185	(40%)	107	(23%)	60	(14%)
Eastern Europe	10	(08%)	10	(08%)	2	(01%)	0	(00%)
C.I.S.	49	(21%)	48	(23%)	25	(12%)	15	(07%)
Aral Sea Basin	46	(86%)	70	(89%)	66	(86%)	62	(86%)
Middle East	168	(95%)	355	(98%)	334	(94%)	309	(91%)
North Africa	128	(80%)	224	(86%)	212	(83%)	191	(79%)
East Africa	54	(31%)	127	(33%)	127	(33%)	121	(33%)
Western Africa	29	(14%)	77	(17%)	72	(17%)	69	(17%)
Central Africa	3	(04%)	8	(05%)	8	(05%)	8	(05%)
Southern Africa	21	(19%)	73	(36%)	65	(33%)	40	(20%)
Australia	9	(39%)	14	(44%)	5	(16%)	3	(12%)
Japan (only)	71	(57%)	67	(55%)	45	(37%)	37	(32%)
China +	453	(34%)	676	(41%)	636	(40%)	565	(37%)
South Asia	539	(44%)	1414	(77%)	1325	(73%)	728	(43%)
Southeast Asia	140	(31%)	287	(46%)	229	(37%)	192	(33%)

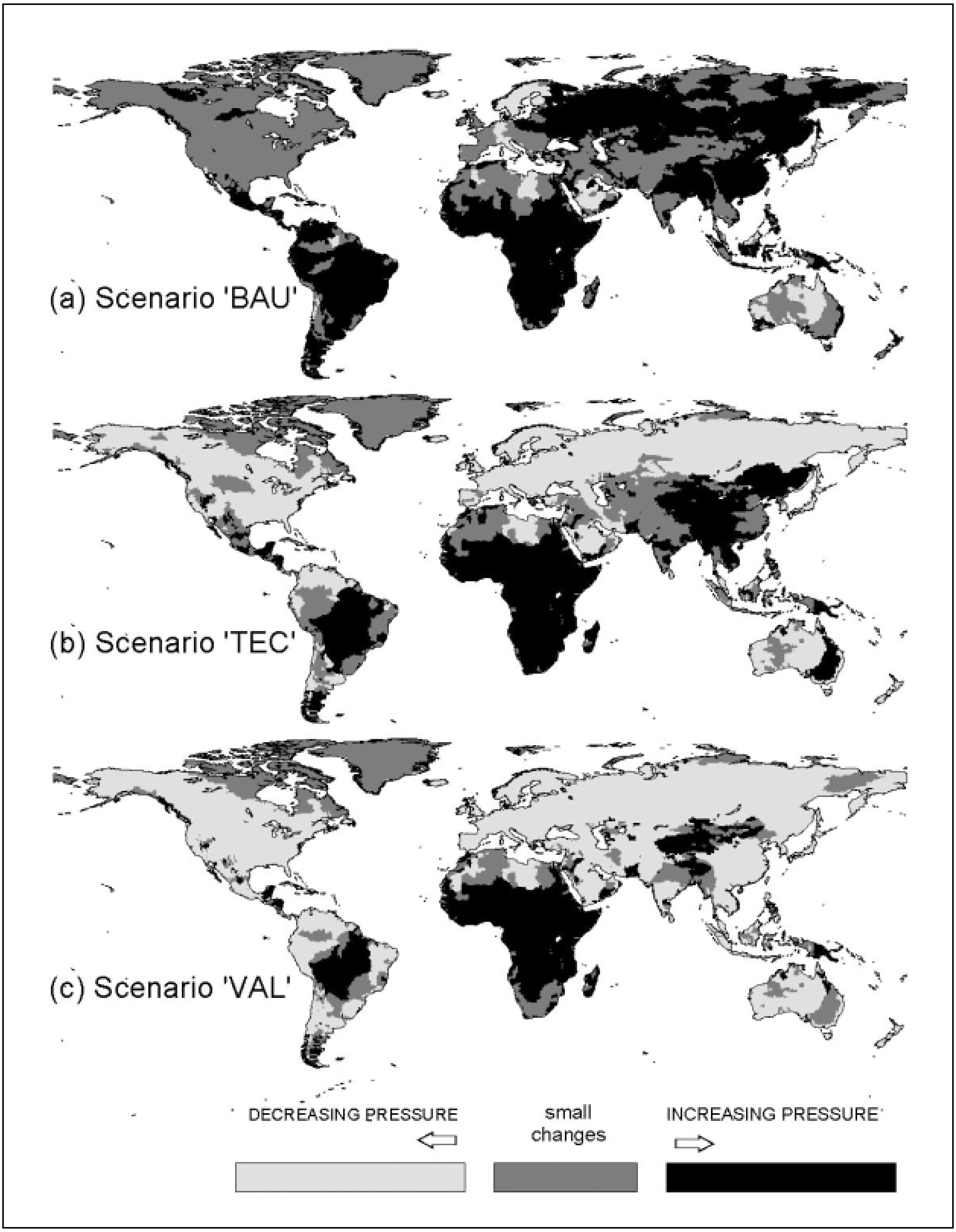

Figure 10. Comparison of scenarios: change in stress on water resources between 1995 and 2025 (a) BAU scenario, (b) TEC scenario, (c) VAL scenario. "Increasing" and "decreasing" pressure indicates an increase or decrease in annual water withdrawals within a river basin, respectively. A "small change" indicates that future withdrawals are within ± 10% of current levels.

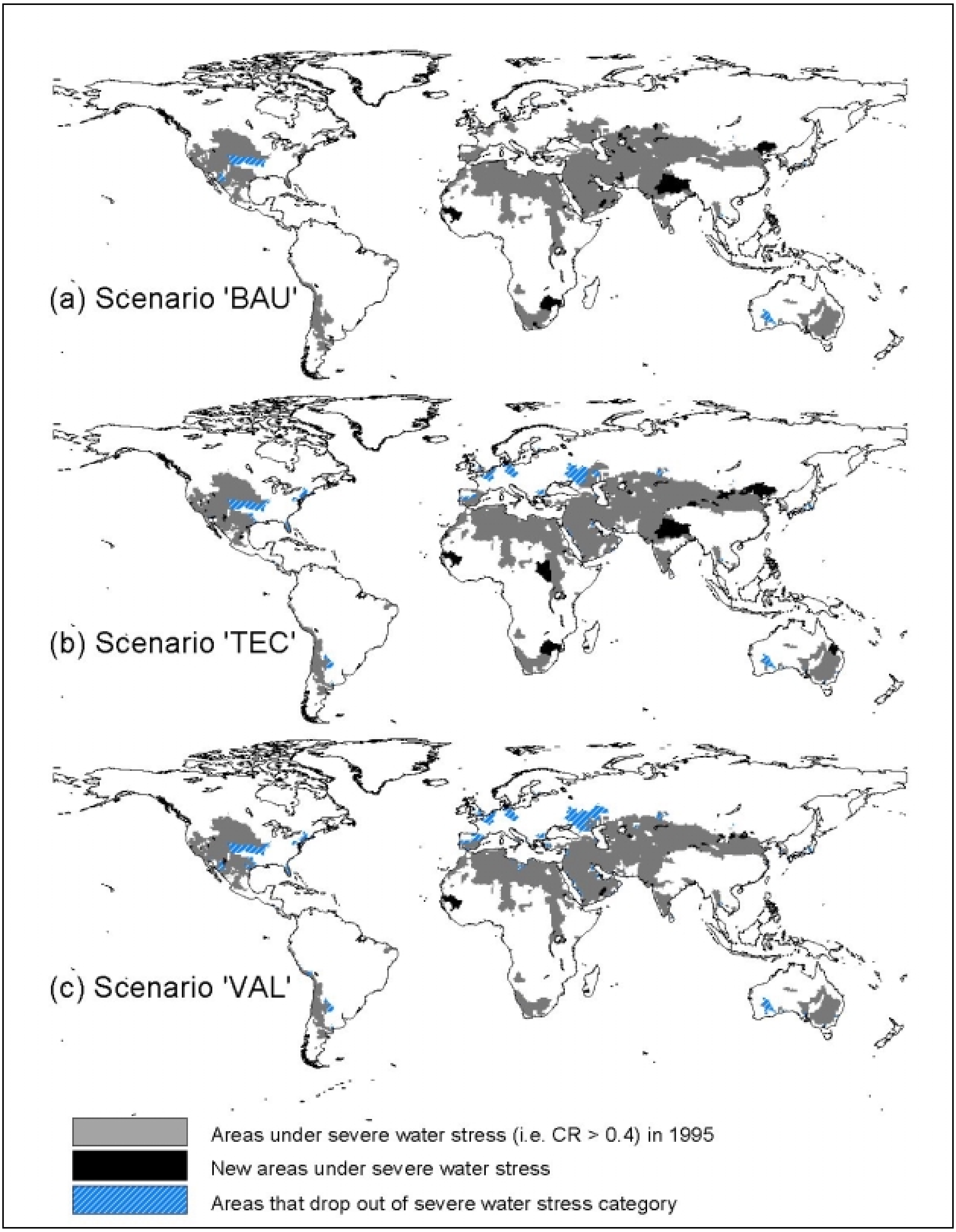

Figure 11. Comparison of scenarios: change in area with severe water stress (CR > 0.4) between 1995 and 2025.

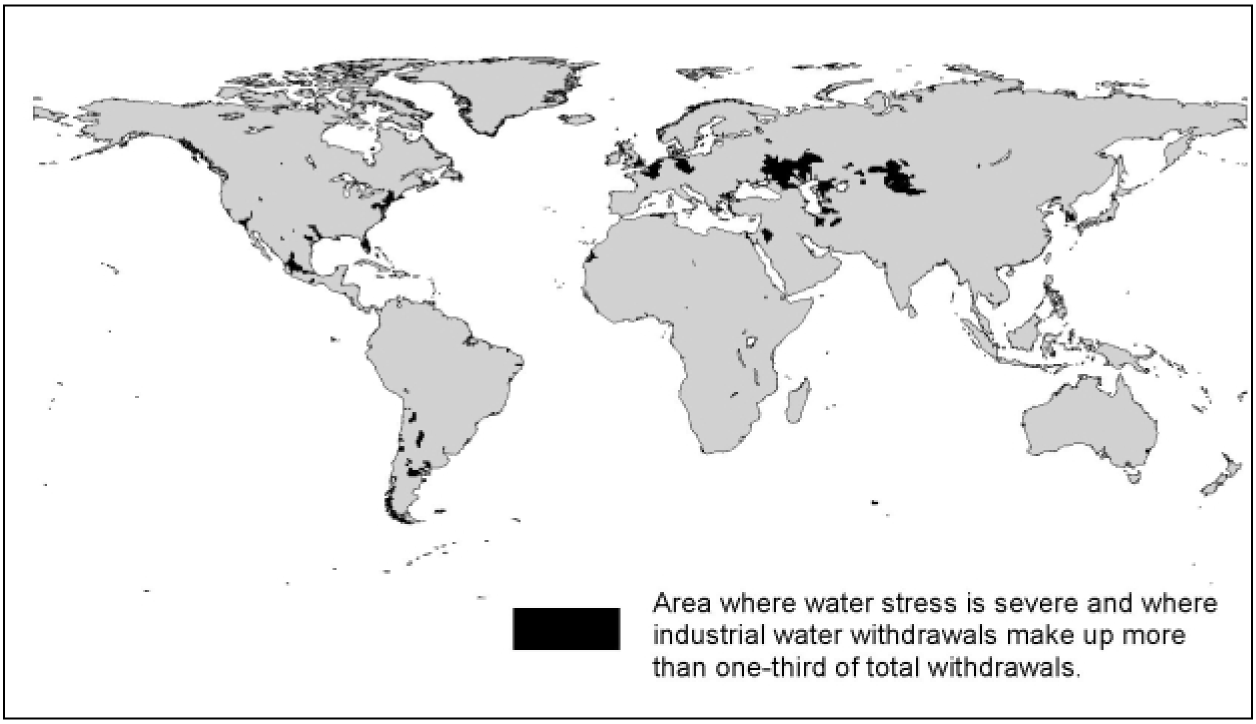

Figure 12. Areas under severe water stress (CR > 0.4) with high industrial water withdrawals in 2025 under the BAU scenario.

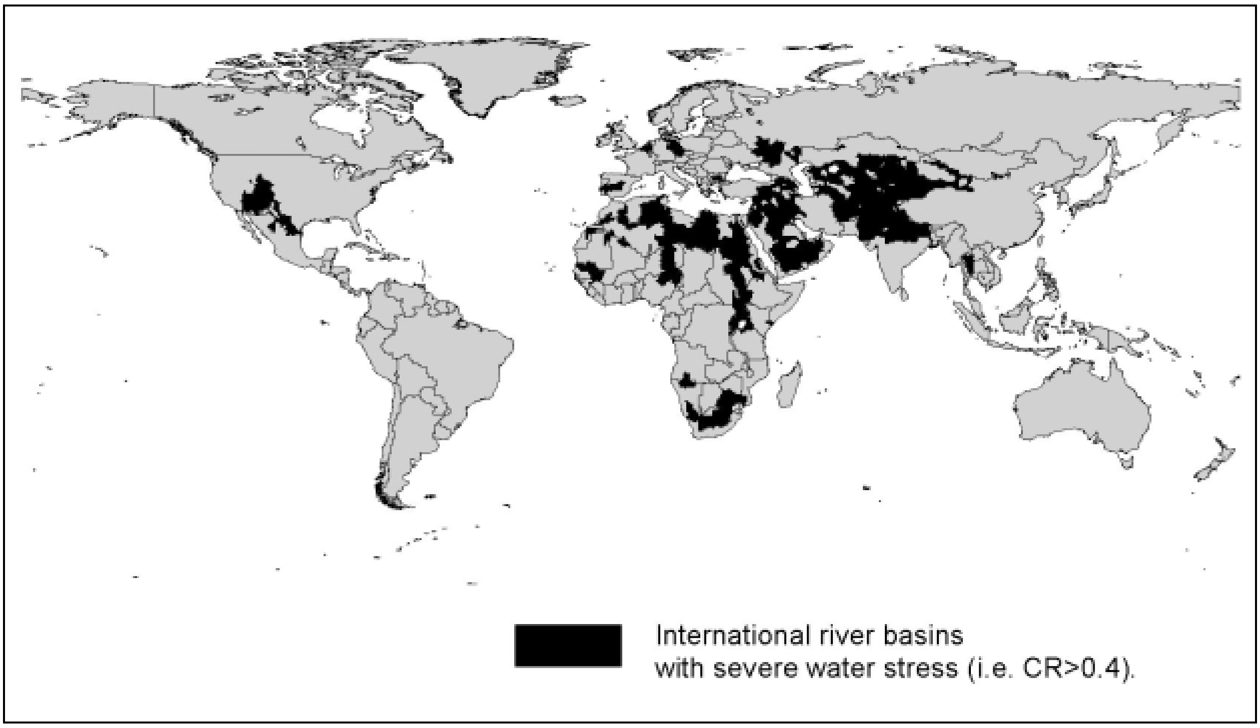

Figure 13. International river basins under severe water stress (CR > 0.4) in 2025 under the BAU scenario.

5. Alternative Scenarios to Business-as-Usual

5.1 General Assumptions

Two scenarios were developed as alternatives to the BAU scenario – "Technology, Economics, and Private Sector" (TEC) and "Values and Lifestyles" (VAL). As compared to the Business-as-usual scenario, they assume a break in current trends up to 2025. They are also *normative* scenarios in that they are designed to achieve a particular goal, and their assumptions are selected so that this goal can be achieved. Their aim is to demonstrate how basic economic needs and development goals can be satisfied within the bounds of current water resources. Both scenarios specify actions to reduce humanity's pressure on global water resources, but these actions come from different directions. To quote from the "storylines" of these scenarios:

a) The scenario "Technology, Economics, and Private Sector" (TEC) has a "worldview that is optimistic about the free market system (and) the potential of new technologies … Water pricing, or cost recovery for services, leads to … increased capital investment, and reduced demands" (Gallopin and Rijsberman, 1999). National income is higher on average than in the BAU scenario, but lower in some regions (Table 3 and Appendix B).
b) The "Values and Lifestyles" (VAL) scenario assumes "that a strong commitment to avert a water crisis will emerge … with efforts focused on reaching a set of global and regional targets. The emphasis is on … the importance of human values … A major effort is made to make the best existing technologies widely available" (Gallopin and Rijsberman, 1999). As compared to the BAU scenario, national income is lower in the richer industrialized regions, but much faster elsewhere (Table 3 and Appendix B).

5.2 Assumptions in the Domestic and Industrial Sectors

The assumptions of the TEC and VAL scenarios can be translated as either new rates of structural change or technological change of water use. The question is, how much of each? Because the TEC scenario is more oriented towards the private sector, and the VAL scenario towards behavioral changes, we assume that technological changes will be stronger in TEC, and structural changes in VAL.

What should be the rate of technological change in the TEC scenario? As a reference point we use the BAU scenario which assumes that technological change leads to a steady 2.0 % per year improvement in water efficiency up to 2005[15]. This slows to 1.0% after 2005, following current trends in many areas of technology. By contrast, increased water pricing and other economic signals under the TEC scenario stimulate greater water conservation efforts in households and businesses. Hence, improvements in water efficiency accelerate from 2.0 to 3.0 % per year after 2005. Meanwhile, the price signals are not as strong in the VAL scenario, and so efficiency improvements are somewhat slower, maintaining a steady 2.0% per year increase between 1995 and 2025.

At the same time, the strong global and regional targets adopted in the VAL scenario lead to a radical change in the structure of water use under this scenario – for example, a substantial frac-

[15] The year 2005 is the arbitrary "turning point" in the scenarios of the World Commission on Water for the 21st Century.

tion of water-cooled thermal power plants are replaced by air-cooled thermal power plants and/or by wind- or solar-generated electricity facilities that use water sparingly. Also, a substantial capacity of current water-intensive manufacturing is replaced by low-water using substitutes. For example, there could be far fewer water-intensive paper manufacturers because paper-based publications are replaced by "paper-less" computer communications. As a result, the structural intensity of water use is two-thirds lower in the VAL scenario than in the BAU scenario at the same level of national income (See Section 2.2.2).[16] Some of these structural changes will also take place in the TEC scenario because larger capital investments lead to a more rapid turnover of equipment and facilities, and some of these new facilities will be water-efficient. However, structural changes in the TEC will not be as strong as in the VAL scenario, so the structural water intensity in TEC is assumed to be only one-third (rather than two-thirds) lower than the BAU scenario.

5.3 Assumptions in the Agriculture Sector

One of the main aims of the TEC and VAL scenarios is to alleviate world poverty and hunger. Accordingly, the International Food Policy Institute (IFPRI) and the International Water Management Institute (IWMI) elaborated scenarios of food production consistent with this goal IFPRI, 1999; IWMI, 1999). Of particular relevance to estimating future water uses, they estimated the future extent of irrigated land and made assumptions about future irrigation water efficiency. To summarize some of their main points:

1. The TEC scenario assumes a rapid increase of investments in agricultural development and in the water infrastructure needed for this development. Consequently, crop yields grow faster than in the BAU scenario, and irrigated land grows globally by 25% (with a strong country-to-country variation ranging from a 24% decrease (in Saudi Arabia) to a 122% increase (in Brazil)). The field efficiency of irrigation also improves much faster than in the BAU scenario (Table 3). Under TEC the global calorie availability per capita increases by 11 %, but the estimated number of malnourished pre-school children in 2025 is still 102 million, only slightly below BAU.

2. Investments also increase under the Values and Lifestyles scenario (VAL), but they focus more on agricultural development in developing countries. More emphasis is also given to "sustainable" agricultural and water management. The greater attention to sustainable lifestyles also results in a slower growth in meat consumption with increasing income. This translates into a smaller demand for feed and forage as compared to the other scenarios. The net result of these changes is a much smaller (5%) increase in global irrigated area, but again with wide variations between countries (ranging from a 100% decrease (for Saudi Arabia) to a 56% increase (in Benin and Burkina Faso)). Under the VAL scenario, global food indicators are much more favorable than in BAU, with calorie availability per capita increasing between 1995 and 2025 by 25 %, and the estimated number of malnourished pre-school children dropping to 61 million.

[16] This assumption is implemented by modifying the curves in the Water Use model that show the change in structural water intensity with national income (GDP/cap-year). (Structural water intensity is the per unit water use in the domestic and industrial sectors due to structural rather than technological changes) The VAL scenario assumes that this structural water intensity is two-thirds lower than the BAU scenario at the same national income.

.

5.4 Water Withdrawals

5.4.1 Industrialized Countries

The strong structural and technological changes assumed in these scenarios have an important influence on domestic and industrial water use in industrialized countries. Domestic water intensity is 36 to 69 % lower than in 1995 (dependent on the scenario), and industrial intensities 74 to 83% lower. Coupling these lower intensities with assumed changes in population, national income and electricity production, results in sharp decreases in overall domestic and industrial withdrawals (Figure 9). In the agricultural sector, improved irrigation field efficiency lowers water intensity from 970 mm (global mean) in 1995 to between 730 and 810 mm in 2025. This is offset somewhat by the large expansion of irrigated land in the TEC scenario, so that water withdrawals only decrease by 6% from 1995 to 2025. In the VAL scenario, irrigated land does not expand as much, and therefore agricultural water withdrawals sink by 16%. The net effect of these trends is to decrease overall withdrawals in industrialized countries between 1995 and 2025 by 37% in the TEC scenario and 48% in the VAL scenario (Figure 9).

5.4.2 Developing Countries

The situation is somewhat different in developing countries. The high growth in national income tends to push up water use per capita in the domestic sector (see Section 2.2.1) but the assumptions about structural and technological change tend to push it down. These factors cancel each other such that the domestic water intensity stays roughly constant, and still far below the intensity of domestic water use in Western Europe in 1995 (at approximately 105 m^3 per capita per year). Nevertheless, both the TEC and VAL scenarios assume that every developing country achieves a minimum domestic water use adequate to meet basic needs (i.e. of 40 l per capita per day or 14.6 m^3 per capita per year, Appendix A).

The industrial sector in developing countries experiences much stronger decreases in water intensity than the domestic sector because the water use per unit production was already decreasing in 1995 in many regions**.** The water intensity decreases from 68.7 m^3 per MWh in 1995 to 16.7 m^3 per MWh in 2025 in the TEC scenario and 10.0 m^3 per MWh in the VAL scenario. Despite the large increase in electricity needed to power the economic growth of developing countries, there is an overall decrease in industrial withdrawals from 1995 to 2025 (Figure 9).

As in industrialized countries, the increase in water use efficiency in the agricultural sector is offset by the increase in irrigated area in most countries. Hence, in the TEC scenario, where a large expansion in irrigated agriculture occurs, agricultural withdrawals increase slightly over 1995 (by about 4%). In the VAL scenario, where only a small expansion in area occurs, withdrawals decrease by 11% between 1995 and 2025 (Figure 9).

5.4.3 Global Results

Globally, despite the strong economic growth and increase in material well-being implied in the TEC and VAL scenarios, the intensity of domestic water use declines from 60.7 m^3 per capita per year in 1995 to 53.7 m^3 per capita per year in 2025 under the TEC scenario, and to 45.2 m^3 per capita per year under the VAL scenario. This reverses the historic trend in which household water use per capita has been rising globally. By comparison, the domestic water intensity in the

BAU scenario is 108.8 m^3 per capita per year. After taking into account changes in population and economy, global domestic withdrawals increase by 22% in the TEC scenario, and decrease slightly in the VAL scenario (Appendix B).

Industrial water intensities plummet from 60.2 in 1995 to between 9.7 and 15.8 m^3 per MWh in 2025, and overall industrial withdrawals shrink by 42 to 63%. In the agricultural sector, a sum of the trends of industrialized and developing countries leads to a slight increase in agricultural water withdrawals in the TEC scenario, and a 20% decrease in the VAL scenario. Summed together, the trends in the different sectors add up to a 4% decrease in global withdrawals in the TEC scenario and 27% in the VAL scenario (Figure 9).

5.5 Stress on Water Resources

As we have discussed, water withdrawals decrease substantially in industrialized countries under the TEC and VAL scenarios. Because of this, the pressure on water resources decreases significantly in most industrialized countries (Figure 10). By contrast, pressure increases in large parts of Brazil, Africa and Asia because of the increase in domestic and industrial water withdrawals in some areas, and the expansion of irrigated area and water requirements in other areas. As in the case of the BAU scenario, the increase in withdrawals in Africa and Latin America occur mostly in water-rich areas, so that the area under severe water stress expands only from 36.4 million km^2 in 1995 to 37.7 km^2 in 2025 in the TEC scenario (Figure 11). As mentioned earlier, the problem in these regions may not be water shortages, but rather the need to rapidly expand water infrastructure to meet increasing demands.

Because irrigation area expands much less in the VAL scenario than in the TEC scenario, the pressure on water resources in the VAL scenario also decreases over a much larger area, especially over parts of Asia and the Middle East (Figure 10c). The area under severe water stress declines to 33.9 km^2 in 2025. Despite the reduction in pressure on water resources in the TEC and VAL scenarios, the growth in population leads to an increase in the number of people living in water-short areas (CR > 0.4) from 2.1 billion in 1995 to 3.5 billion under the TEC scenario, and to 2.6 billion even under the VAL scenario.

5.6 Summing Up the Alternative Scenarios

In total, the TEC and VAL scenarios reduce the intensities of water use in the domestic, industry and agricultural sectors, and thereby reduce the pressure on water resources brought on by population growth and increasing material well-being. How is this accomplished? An important lesson from the scenarios is that improvements in the efficiency of water use in the domestic and industry sectors are necessary but insufficient to avoid water scarcity in many river basins around the world. This is because population and economic growth increases the demand for water, and this partly counteracts the improvements in water use efficiency. Calculations of domestic water withdrawals in China (Figure 14) illustrate this point. The first bar shows 1995 water withdrawals, and the second shows what withdrawals would be in 2025 under the BAU scenario if no efficiency improvements were assumed. The third bar shows the BAU scenario with efficiency improvements. Hence, these efficiency improvements have a significant effect on lowering withdrawals, although the withdrawals are still substantially above 1995 levels because of economic and population growth. The fourth bar shows results for the VAL scenario which combines efficiency improvements with strong reductions in water use because of structural changes. The point is, that not only technological improvements but also basic structural changes (such as a shifting from power plants that require water cooling to those that do not) will be needed to reduce current water withdrawals and their pressure on water resources.

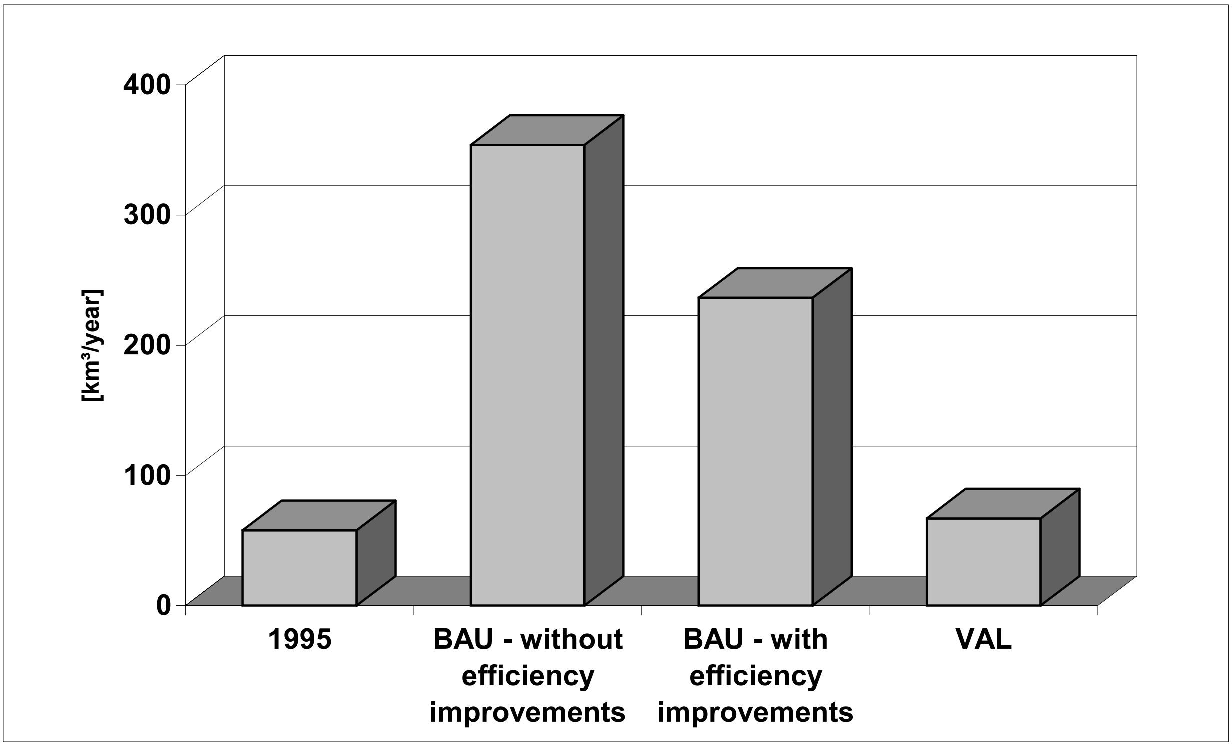

Figure 14. Sensitivity analysis of computed domestic water withdrawals in China.

Yet despite the lessening of pressure on water resources in the TEC and VAL scenarios, the area of severe water stress does not change very much. What then is needed to reduce this area and achieve a sustainable water world? The core issue is the amount of water used for irrigation, because this is and will continue to be the principal user of water in most water-short areas of developing countries. An important point is that irrigation dominates other water sectors even though irrigation water efficiency is assumed to improve between 1995 and 2025. As a result of these improvements, the net withdrawals for irrigation decrease even though irrigation area increases in most countries. As in the case of the domestic and industrial sectors, even rapid improvements in water efficiency will not avoid water scarcity. Apparently, fundamental "structural" changes are also needed in the world's agricultural system – These could include:

- Slowing down the trend towards excessive meat-consumption in order to slow the growth of irrigated land needed for livestock feed.
- Shifting, where possible, from irrigated crops to rainfed crops.
- Moving irrigated farmland from river basins under severe water pressure to those richer in water. This may require a shift in the type of crops that are grown and a willingness to pay for the implicit value of water in agricultural products.

Of course, these will not be easy actions to undertake, but they may be necessary to address current and future water scarcity.

6. Results for Selected Regions

Regional results are summarized in Tables 4 and 5, and in Appendix B. Here we briefly describe the scenarios for three representative regions.

6.1 Sub-Saharan Africa

Under the Business-as-Usual scenario, domestic water withdrawals in Sub-Saharan Africa increase substantially, from about 10 km^3 per year in 1995 to 42 km^3 per year in 2025. This is because higher income is presumed to lead to higher per capita water use, even though technology tends to improve the efficiency in water use. For example, in 2025, domestic water use in West Africa would be 34 m^3/cap-year which is above the 1995 value by a factor of 2.2, but still far below the Western European level today (1995: 105 m^3/cap-year). In this part of Africa, industrial output, and hence water use, also increases from about 3 to 15 km^3/year between 1995 and 2025. Because of abundant rainfall, it is likely that there will – in theory - be enough water to cover the increase in domestic and industrial water use. Instead, the question probably is whether water distribution systems can be expanded fast enough to fulfill the needs of growing population and industry. To cover the growth in water withdrawals noted above, the capacity of municipal water withdrawals (and perhaps wastewater treatment) need to be expanded by more than 5 % per year, and industrial withdrawals by about 7 % per year.

6.2 South and East Asia[17]

Under the BAU scenario irrigated area in this region remains at its current level (expanding only in India), while irrigation efficiency improves. The net effect is a decrease in water used for irrigation in this region, i.e. from 1359 to 1266 km^3 per year. At the same time, strong economic growth between 1995 and 2025 leads to more material wealth and greater water use in each household which increases domestic water withdrawals from 114 to 471 km^3 per year. Since industry also requires larger quantities of water, withdrawals in this sector increase as well, from 153 to 263 km^3 per year.

The sum of these trends is an overall increase in total water withdrawals between 1995 and 2025. Hence, the pressure on water resources becomes even greater than already experienced in 1995, when about 6.5 million km^2 of river basin area was under severe water stress. This increases to 7.9 million km^2 in 2025.[18] The number of people living in these areas also grows tremendously from 1.1 to 2.4 billion during this period.

Under the TEC scenario, withdrawals do not grow as rapidly as in the BAU scenario because of structural changes and accelerated improvements in water efficiency. Nevertheless, they do show a net increase compared to 1995. Only in the VAL scenario do total withdrawals decrease be-

[17] This region includes South Asia (with Bangladesh, India, Nepal, Pakistan, Sri Lanka), China+ (with China, Hong Kong, North Korea, Laos, Macau, Mongolia, Vietnam), and Southeast Asia (with Bhutan, Brunei, Cambodia, East Timor, Indonesia, South Korea, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan).

[18] Part of this increase has to do with the Ganges Basin, which was slightly under the threshold for high water stress (CR = 0.396) in 1995, but exceeds this threshold in 2025 under the BAU scenario.

cause of a decline in water intensity in the industrial sector, and because improvements in irrigation efficiency outweigh the small expansion of irrigated land.

6.3 Europe[19]

The total withdrawals of water in Europe are growing slowly or not at all as households, industry and agriculture become more water-efficient. The per capita use of water in households goes up slightly with the economic growth of the Business-as-Usual scenario between 1995 and 2025, while the amount of water used by industry per megawatt-hour goes down because of greater recycling and other efficiency improvements. The amount of irrigated area stabilizes and new technologies improve the efficiency of irrigation systems so that there is also a decline in the amount of water used for irrigation during this period.

Sharp reductions in both domestic and industrial intensities are seen in the TEC and VAL scenarios. Despite the expansion of irrigated area in the TEC scenario, agricultural water withdrawals still go down because of water efficiency improvements. Nevertheless, the pressure on water resources remains high in some areas because of the density of population and industrial activity.

[19] This region includes Western Europe (with Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Iceland, Ireland, Italy, Luxembourg, Malta, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom) and Eastern Europe (with Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Macedonia, Poland, Romania, Serbia and Monte Negro, Slovak Republic, Slovenia).

7. The Robustness of the Water Scarcity Indicator

In this paper we employ the commonly used "criticality ratio (CR)" (annual withdrawals over water availability) as an indicator of the intensity of water stress in a river basin. As previously explained, we assume that a value above 0.4 indicates a "severe level of stress". We also explained that the effects of a severe level of water stress are likely to be different in different parts of the world – in industrialized countries and some desert areas a CR value above 0.4 indicates strong competition for water, which does not necessarily trigger frequent water crises, whereas in most developing countries this value may well indicate ongoing, frequent water emergencies. Since this threshold is based more on experience than on hard data, the question arises, how sensitive are the conclusions derived in this paper to the selection of CR > 0.4 as a threshold? To answer this we carryout a sensitivity analysis in which we recompute the area of river basins in the severe water stress category assuming different thresholds values for this category. Some experts believe that 0.4 is too low a threshold, and that water resources can be used much more intensely – therefore, we set an upper bound of CR > 0.6. Others believe that freshwater ecosystems cannot remain healthy if the waters in a river basin are used as intensely as indicated by CR > 0.4. Therefore, as a lower bound we use CR > 0.2.

Figure 15 compares results for CR > 0.2, 0.4, and 0.6 for 1995 and for 2025 under the BAU and VAL scenarios. This sensitivity analysis shows that lowering the threshold from CR > 0.4 to CR > 0.2 results in many additional critical areas (Figure 15a). The area that would be labeled "severe water stress" increases by 26% to 30% depending on the scenario. The number of people living in "severe water stress" areas would also be higher (Figure 15b). Increasing the threshold from CR > 0.4 to CR > 0.6 makes a smaller relative change in the estimate of area in the severe water stress category (9 to 12%). Of greater importance, the differences *between* scenarios remain about the same in this sensitivity analysis. Hence, conclusions about global changes in the area of severe water stress with respect to 1995 appear to be fairly robust.

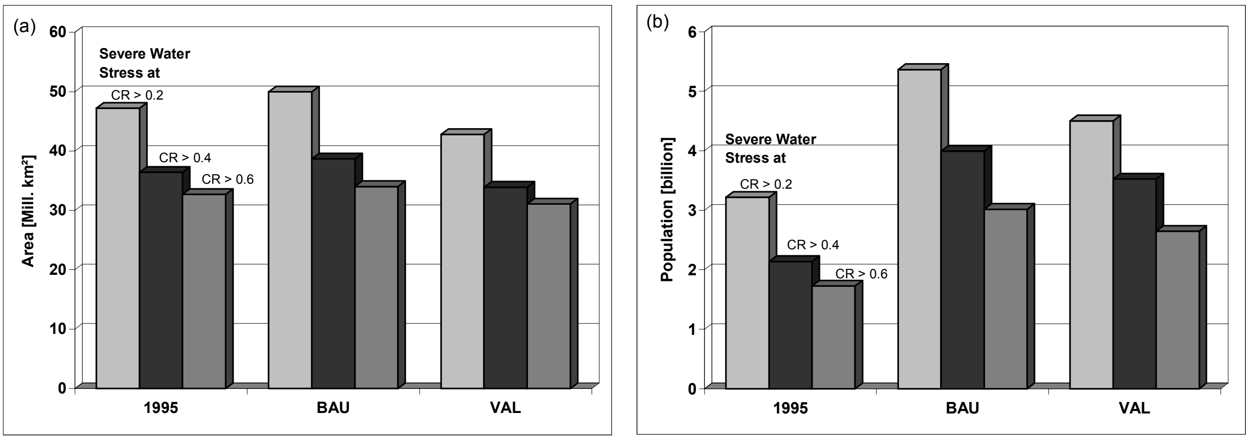

Figure 15. Sensitivity analysis of CR for 1995, 2025 under the BAU scenario, and 2025 under the VAL scenario: (a) Comparison of areas with severe water stress. (b) Same as "(a)" but for population living in these areas.

8. Summary

The future global water situation and developments in the water sector until 2025 have been examined by analyzing three scenarios: “Business-as-usual” (BAU) based on current trends, and two alternative scenarios to the BAU scenario – the “Technology, Economics, and Private Sector” scenario (TEC), and the “Values and Lifestyles” scenario (VAL) .

An important finding of the BAU scenario is that the great contrast in the water situation between industrialized and developing countries is likely to continue. Water withdrawals in most industrialized countries decline and therefore the pressure put on water resources also declines. Meanwhile, withdrawals grow in most developing countries and increase the pressure on their water resources. Between 1995 and 2025 the areas affected by “severe water stress” expand and intensify, growing globally from 36.4 to 38.6 million km^2. The increase is especially significant in Southern Africa, Western Africa and South Asia. The number of people living in these areas also grows from 2.1 to 4.0 billion people. In river basins under severe water stress there will be strong competition for scarce water resources between households, industry and agriculture.

Another important finding of the BAU scenario is that future industrial and economic growth in regions under severe water stress may be limited by heavy competition with municipalities and agriculture for scarce water resources. Furthermore the BAU scenario shows that many of the world’s internationally shared river basins will be in the high or very high stress categories in 2025. Indeed, 33 % of the total area of international river basins will be in either one of these categories. The competition for these water resources could be an ongoing source of tension between nations.

In the two alternative scenarios very strong assumptions about policies and behavior that significantly reduce the intensity of water use have been made. One important feature of these scenarios is that they result in important breaks in current trends. First of all, every developing country achieves a minimum domestic water use adequate to meet basic needs (40 l per capita per day). Second, water withdrawals drop very sharply in industrialized countries (compared to the BAU scenario) and the pressure on water resources in these countries is also greatly reduced. Finally, under the VAL scenario, water withdrawals in developing countries stop growing even though their economies and material well-being grow tremendously.

Another important feature about the TEC and VAL scenarios is that some current trends may continue under these scenarios. For example, total water withdrawals continue to grow substantially in many parts of Africa, Latin America and Asia because of increasing population, and because of economic growth and the material aspirations that come with it. This, however, does not lead to a large increase in the areas under severe water stress in Africa and Latin America because this growth occurs mostly in water-rich areas. In these regions the problem may not be water shortages, but instead the need to rapidly expand water infrastructure to accommodate increasing water demands.

In essence, both the BAU and the other scenarios examined here imply that the current serious water situation could continue at least through 2025. Thus, decisive action will be needed to address current and future water scarcity. These must include not only efficiency improvements, but also general structural changes in how we use water.

Acknowledgments

This work was carried out with support of the World Commission on Water for the 21st Century. However this report does not necessarily reflect the views of the Commission. The authors are in particular grateful to Frank Rijsberman, William Cosgrove and Subhrendu Gangopadhyay of the Commission Secretariat for their support. The authors also acknowledge the cooperative atmosphere within the Scenario Panel of the Commission which led to a fruitful exchange of information between them and especially Ken Strzepek and Gilberto Gallopin of Stockholm Environment Institute, Mark Rosegrant and Claudia Ringler of the International Food Policy Research Institute, and David Molden of the International Water Management Institute.

The authors are also indebted to their colleagues at the Center for Environmental Systems Research, University of Kassel, in particular Frank Kaspar, Bernhard Lehner, Petra Döll, and Janina Onigkeit for assistance with WaterGAP calculations.

References

Alcamo, J., Döll, P., Kaspar, F., Siebert. S. (1997): Global change and global scenarios of water use and availability: an application of WaterGAP 1.0. Report A9701, Center for Environmental Systems Research, University of Kassel, Kurt Wolters Strasse 3, D-34109 Kassel, Germany.

Alcamo, J. and Kaspar, F. (1998): Coupled simulation of changes in climate, land cover and water availability on the global level. Presented at the International Geosphere-Biosphere Programme Conference on the Earth´s Changing Land, Barcelona, Spain. March, 1998.

Batjes, N.H. (1996): Development of a world data set of soil water retention properties using pedotransfer rules. G Geoderma, 71, 31-52.

Bergström, S. (1994): The HBV model. In V.P. Singh (ed): Computer Models of Watershed Hydrology. Water Resources Publications: 443-476.

Carr, J.E., Chase, E.B., Paulson, R.W., Moody, D.W. (1990): National Water Summary 1987. USGS Water Supply Paper 2350. USGS: Denver.

Deardorff, J. W. (1978): Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. Journal Geophysical Research 86C, 1889-1903.

Döll, P., Kaspar, F., Lehner, B. (2000): The hydrologic calculations of WaterGAP 2.0. Report of the Center for Environmental Systems Research, University of Kassel, Germany. Forthcoming

Döll, P., Siebert, S. (1999a): A digital global map of irrigated areas. Submitted to International Commission on Irrigation and Drainage Journal.

Döll, P., Siebert, S. (1999b):Global modeling of irrigation water requirements. Submitted to Water Resources Research.

Döll, P., Kaspar, F., Siebert, S., Alcamo, J. (1999). Modeling of global water availability and water use under drought conditions. Paper presented to IUGG General Assembly, IAHS Symposium 1: Hydrological extremes: understanding, predicting, mitigating. Birmingham, U.K. July, 1999.

Falkenmark, M., Lindh, G. (1974): How can we cope with the water resources situation by the year 2050? Ambio (3): 3-4.

Falkenmark, M, Lindh, G. (1993): Water and economic development, in Gleick, P., Water in Crisis. Oxford University Press. 473 pp.

German Federal Statistical Agency, Federal Republic of Germany (1996): Statistical Yearbook. Metzler-Poeschel.

Gallopin, G., Rijsberman, F. (1999): Three global scenarios. Report to the World Commission on Water for the 21st Century.

GRDC (Global Runoff Data Center): Observed river discharges. Global Runoff Data Center, D-56068 Koblenz, Germany.

Grübler, A. (1998): Technology and global change. Cambridge University Press: Cambridge, U.K. 452pp.

IFPRI (International Food Policy Institute) (1999): World water vision scenarios: consequences for food supply, demand, trade, and food security. IFPRI, Washington. D.C.

IRRI (International Rice Research Institute) (1988): World Rice Statistics 1987, IRRI, Manila, The Philippines, and http://www.riceweb.org/.

IWMI (International Water Management Institute) (1999): World water vision scenarios.

Klepper, O,, van Drecht, G. (1998): WARiBaS, Water Assessment on a River Basin Scale; A computer program for calculating water demand and water satisfaction on a catchment basin level for global-scale analysis of water stress. Report Number 402001009 of the National Institute of Public Health and the Environment (RIVM), June 1998. RIVM, P.O. Box 1, 3720 BA Bilthoven, The Netherlands.

Möhle, K.-A. (1988): Water use, water use development, rational use of water in public water facilities and services. Report of the German Environmental Agency UBA FB 87 052: Berlin.

Probst, J.L., Tardy, Y. (1987): Long range streamflow and world continental runoff fluctuations since the beginning of this century. Journal of Hydrology., 94, 289-311.

Raskin, P. (ed.) (1997): Comprehensive assessment of the freshwater resources of the world. Stockholm Environment Institute. Box 2142. S-103 14, Stockholm, Sweden.

Roth, D. (1993): Richtwerte für den Zusatzwasserbedarf in der Feldberegnung, Schriftenreihe der LUFA Thüringen, 6, 53-86.

Shiklomanov, I. (1999): Assessment of water resources and water availability in the world. Report to the World Water Commission, October, 1999. .

Shiklomanov, I. (1997): Assessment of water resources and water availability in the world, Comprehensive Assessment of the Freshwater Resources of the World, Stockholm.

Smith, M. (1992): CROPWAT - A Computer Program for Irrigation Planning and Management, FAO Irrigation and Drainage Paper 46, Rome, Italy.

Solley, W.B., Pierce, R.S., Perlman, H.A. (1998): Estimated Use of Water in the United States in 1995, USGS Circular 1200. (http://water.usgs.gov/public/watuse/)

USGS (U.S. Geological Survey) (1990): National Water Use Summary 1987. USGS Water Supply Paper 2350.

USGS (1999): HYDRO1k Elevation Derivative Database. Eros Data Centre. http://edcwww.cr.usgs.gov/landdaac/gtopo30/hydro/index.html.

van der Leeden, F. (1975): Water Resources of the World - Selected Statistics. Water Information Center, Inc., Port Washington, New York, USA.

Vörösmarty, C.J., Fekete, B.M., Tucker, B.A. (1996): Global River Discharge Database (RivDis V.1.0). Report for UNESCO. University of New Hampshire, Durham, USA.

WRI (World Resources Institute) (1998): World Resources 1998-99. Oxford Press: N.Y. 369 pp.

World Bank (1997): World Development Report 1997. Oxford University Press. 265 pp.

Appendix A: Minimum Water Uses in the Water GAP 2.0 Water Use Model

Assumed minimum water use intensity in the domestic sector:[20]

Developing Countries -- One of the assumptions of the TEC and VAL scenarios is that the basic water needs of the average inhabitant of a developing country will be met. For these scenarios we set a minimum value of 40l/cap-day or 14.6 m^3/cap-year for the domestic water intensity. This value is specified in the qualitative "storylines" of the TEC and VAL scenarios[21].

Industrialized Countries – For certain scenarios, a rather high rate of improvement in water use efficiency is assumed for industrialized countries. As a result, the model sometimes calculates unrealistically low per capita water uses in the domestic sector for some scenarios and countries. In order to avoid this situation, WaterGAP sets a lower limit on per capita water use in industrialized countries. This limit is two times higher than the minimum value specified for developing countries, i.e. 2 x 14.6 m^3/cap-year, or 29.2 m^3/cap-year. This intensity is about 50% of current (1995) domestic water intensity in Germany, and is close to the average European level in 1950. It is also close to the water use for a "fair level of domestic supply" (100 l/cap-day or 36.5 m^3/cap-year) suggested by Falkenmark (1993). Although this limit is highly uncertain, we note in Section 2.2.3 that this uncertainty has a small influence on the main conclusions of this paper.

[20] "Industrialized" countries here are the "high" income countries listed in World Bank (1997), and "developing" countries are all remaining countries.

[21] Gallopin and Rijsberman (1999).

Appendix B: Summary table of regional assumptions and results

The World Today (1995)	Population	Annual Change GDP/cap	Annual Change Elec.Prod	Total Water Withdrawals	Domestic Water Withdrawals	Industrial Water Withdrawals	Agricultural Water Withdrawals
	[1000]	*[%]*(*)	*[%]*(*)	*[km^3]*	*[% of Total]*	*[% of Total]*	*[% of Total]*
WORLD	**5,678,130**	**-**	**-**	**3,572**	**(10%)**	**(21%)**	**(69%)**
North America	300,496	-	-	533	(12%)	(48%)	(40%)
Central America	153,996	-	-	126	(08%)	(22%)	(71%)
South America	317,477	-	-	157	(18%)	(16%)	(65%)
Western Europe	444,632	-	-	290	(16%)	(42%)	(42%)
Eastern Europe	129,050	-	-	85	(12%)	(43%)	(45%)
C.I.S.	231,619	-	-	120	(16%)	(52%)	(32%)
Aral Sea Basin	53,942	-	-	154	(02%)	(09%)	(89%)
Middle East	177,471	-	-	198	(05%)	(05%)	(90%)
North Africa	160,387	-	-	98	(08%)	(06%)	(86%)
East Africa	173,266	-	-	34	(07%)	(01%)	(92%)
Western Africa	207,217	-	-	13	(24%)	(08%)	(68%)
Central Africa	72,455	-	-	2	(46%)	(10%)	(44%)
Southern Africa	106,127	-	-	20	(17%)	(09%)	(74%)
Australia	23,202	-	-	27	(12%)	(27%)	(61%)
Japan (only)	125,068	-	-	89	(19%)	(32%)	(49%)
China +	1,329,580	-	-	611	(11%)	(16%)	(74%)
South Asia	1,222,870	-	-	832	(03%)	(03%)	(94%)
Southeast Asia	449,270	-	-	183	(14%)	(18%)	(68%)

Scenario TEC (2025)	Population	Annual Change GDP/cap	Annual Change Elec.Prod	Total Water Withdrawals	Domestic Water Withdrawals	Industrial Water Withdrawals	Agricultural Water Withdrawals
	[1000]	*[%]*(*)	*[%]*(*)	*[km^3]*	*[% of Total]*	*[% of Total]*	*[% of Total]*
WORLD	**7,889,660**	**-**	**-**	**3,412**	**(12%)**	**(13%)**	**(75%)**
North America	373,344	3.32	0.25	323	(14%)	(25%)	(61%)
Central America	226,994	1.12	4.57	140	(07%)	(21%)	(72%)
South America	442,665	1.80	4.04	162	(15%)	(15%)	(70%)
Western Europe	466,614	3.32	1.12	197	(16%)	(23%)	(62%)
Eastern Europe	125,850	1.42	1.11	59	(12%)	(29%)	(59%)
C.I.S.	207,391	2.13	1.95	82	(19%)	(37%)	(43%)
Aral Sea Basin	76,917	2.34	3.60	144	(04%)	(08%)	(89%)
Middle East	356,947	1.31	4.97	183	(06%)	(06%)	(88%)
North Africa	256,618	4.07	7.99	115	(13%)	(11%)	(76%)
East Africa	379,583	3.77	14.53	52	(23%)	(07%)	(70%)
Western Africa	433,455	3.92	12.78	29	(41%)	(23%)	(36%)
Central Africa	160,004	3.74	11.29	6	(58%)	(21%)	(21%)
Southern Africa	199,115	3.54	6.41	26	(26%)	(08%)	(65%)
Australia	32,281	3.27	1.91	28	(09%)	(11%)	(81%)
Japan (only)	121,066	2.17	0.49	49	(14%)	(20%)	(66%)
China +	1,608,470	4.02	5.43	725	(16%)	(12%)	(72%)
South Asia	1,806,820	3.81	6.47	903	(08%)	(03%)	(88%)
Southeast Asia	615,520	3.35	5.19	190	(12%)	(20%)	(68%)

Scenario BAU (2025)	Population	Annual Change GDP/cap	Annual Change Elec.Prod	Total Water Withdrawals	Domestic Water Withdrawals	Industrial Water Withdrawals	Agricultural Water Withdrawals
	[1000]	*[%]*(*)	*[%]*(*)	*[km^3]*	*[% of Total]*	*[% of Total]*	*[% of Total]*
WORLD	**8,028,630**	**-**	**-**	**4,092**	**(21%)**	**(23%)**	**(56%)**
North America	373,344	2.10	1.16	515	(19%)	(44%)	(38%)
Central America	230,994	1.77	4.48	171	(14%)	(39%)	(47%)
South America	451,678	1.95	4.04	208	(28%)	(26%)	(46%)
Western Europe	466,614	2.10	0.83	269	(21%)	(36%)	(42%)
Eastern Europe	127,983	1.89	1.46	90	(13%)	(48%)	(39%)
C.I.S.	211,267	2.15	1.92	141	(26%)	(49%)	(25%)
Aral Sea Basin	78,915	2.17	3.77	163	(06%)	(17%)	(77%)
Middle East	363,966	1.40	4.17	206	(12%)	(09%)	(79%)
North Africa	261,631	2.06	4.94	114	(18%)	(14%)	(67%)
East Africa	386,594	1.83	10.31	47	(28%)	(08%)	(63%)
Western Africa	442,464	1.96	8.21	31	(49%)	(22%)	(29%)
Central Africa	163,023	1.92	7.72	6	(59%)	(22%)	(18%)
Southern Africa	203,158	1.69	4.31	28	(36%)	(13%)	(51%)
Australia	32,281	2.05	1.83	27	(19%)	(26%)	(54%)
Japan (only)	121,066	0.96	0.76	78	(18%)	(30%)	(52%)
China +	1,641,460	4.20	3.57	813	(33%)	(17%)	(51%)
South Asia	1,843,800	3.49	5.06	952	(17%)	(06%)	(78%)
Southeast Asia	628,385	2.98	4.41	236	(21%)	(31%)	(48%)

Scenario VAL (2025)	Population	Annual Change GDP/cap	Annual Change Elec.Prod	Total Water Withdrawals	Domestic Water Withdrawals	Industrial Water Withdrawals	Agricultural Water Withdrawals
	[1000]	*[%]*(*)	*[%]*(*)	*[km^3]*	*[% of Total]*	*[% of Total]*	*[% of Total]*
WORLD	**7,456,400**	**-**	**-**	**2,593**	**(13%)**	**(11%)**	**(76%)**
North America	340,968	0.98	-0.06	245	(09%)	(20%)	(72%)
Central America	208,995	5.18	5.11	112	(12%)	(18%)	(70%)
South America	408,613	4.07	4.49	128	(18%)	(12%)	(70%)
Western Europe	442,634	1.53	0.64	152	(10%)	(17%)	(73%)
Eastern Europe	121,584	4.37	1.43	49	(10%)	(26%)	(64%)
C.I.S.	201,577	5.13	2.53	70	(28%)	(29%)	(43%)
Aral Sea Basin	71,923	4.50	4.10	116	(05%)	(07%)	(88%)
Middle East	340,905	3.89	5.59	148	(08%)	(05%)	(87%)
North Africa	240,580	6.73	8.67	101	(13%)	(09%)	(78%)
East Africa	363,559	5.92	15.24	46	(23%)	(05%)	(71%)
Western Africa	416,436	6.11	13.64	29	(50%)	(16%)	(33%)
Central Africa	157,992	5.18	12.13	5	(59%)	(18%)	(23%)
Southern Africa	195,071	5.20	7.12	23	(25%)	(11%)	(65%)
Australia	29,255	1.21	0.75	20	(06%)	(08%)	(86%)
Japan (only)	118,064	0.12	-0.19	41	(08%)	(13%)	(79%)
China +	1,514,500	7.69	5.89	519	(16%)	(10%)	(74%)
South Asia	1,705,820	6.65	6.95	645	(11%)	(03%)	(86%)
Southeast Asia	577,915	6.01	5.64	146	(12%)	(17%)	(71%)

(*) until branch-point year 2005 all scenarios follow path of development as shown for BAU scenario, thereafter rates of change specific to scenario apply