Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions

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Abstract New global models provide the opportunity to generate quantitative information about the world water situation. Here the WaterGAP 2 model is used to compute globally comprehensive estimates about water availability, water withdrawals, and other indicators on the river-basin scale. In applying the model to the current global water situation, it was found that about 24% of world river basin area has a withdrawal to availability ratio greater than 0.4, which some experts consider to be a rough indication of "severe water stress"; the impacts of this stress are expected to be stronger in developing countries than in industrialized ones. Under a "business-as-usual" scenario of continuing demographic, economic and technological trends up to 2025, water withdrawals are expected to stabilize or decrease in 41% of world river basin areas because of the saturation of water needs and improvement in water-use efficiency. Withdrawals grow elsewhere because population and economic growth will lead to rising demand for water, and this outweighs the assumed improvements in water-use efficiency. An uncertainty analysis showed that the uncertainty of these estimates is likely to have a strong geographic variability.

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

Estimations globales actuelles et futures, en conditions de continuité, de la disponibilité de l'eau et des prélèvements

Résumé Les nouveaux modèles globaux donnent l'opportunité de générer de l'information quantitative au sujet de la situation hydrologique mondiale. Nous utilisons le modèle WaterGAP 2 pour calculer des estimations à vocation globale de la disponibilité en eau, des prélèvements d'eau et d'autres indicateurs, au niveau des bassins versants. L'application du modèle à la situation hydrologique globale actuelle montre que 24% environ de la surface des bassins versants du monde présentent un rapport entre prélèvement et disponibilité supérieur à 0.4, ce que certains experts considèrent comme une indication grossière d'un "stress hydrique sévère"; les impacts de ce stress étant estimés plus forts dans les pays en voie de développement que dans les pays industrialisés. Selon un scénario de continuité dans les tendances démographiques, économiques et technologiques jusqu'en 2025, les prélèvements d'eau se stabilisent ou diminuent sur 41% de la surface des bassins versants à cause de la saturation des besoins en eau et de l'amélioration de l'efficience de l'utilisation de l'eau. Ailleurs, les prélèvements croissent parce que la croissance démographique et économique augmente les besoins en eau, ce qui surpasse les améliorations supposées dans l'efficience de l'utilisation de l'eau. Une analyse d'incertitude montre que l'incertitude liée à ces estimations présente une forte variabilité géographique.

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

Open for discussion until 1 December 2003

INTRODUCTION

A series of significant international meetings (including, for example, the First World Water Forum, in Marrakech, March, 1997; the Second World Water Forum, in The Hague, March, 2000; and the World Summit on Sustainable Development in Johannesburg, August, 2002) have shown that the issue of global water resources has achieved a central place in discussions about international economic development and environmental policy. Such discussions require, among other things, an overview and assessment of the current and future world water situations. The objective of this paper is to provide quantitative analyses that contribute to the understanding of the world water situation. First, a brief overview is presented of the WaterGAP 2 model, which is used for these analyses. Readers are referred to a companion paper (Alcamo *et al*., 2003) for details about the model development and testing. Next the model is used to analyse the current world water situation. Then model results are examined for a "business-as-usual" scenario of changes in water resources up to 2025. Finally, an analysis of the uncertainty of the model is presented to help evaluate model results.

OVERVIEW OF THE WATERGAP 2 MODEL

Calculations in this paper use the global WaterGAP 2 model (Water – Global Assessment and Prognosis), which was developed at the Centre for Environmental Systems Research of the University of Kassel, Germany, in cooperation with the National Institute of Public Health and the Environment of The Netherlands (RIVM). The WaterGAP 2 model is currently the only model with global coverage that computes both water use and availability on the river basin scale.

The aim of WaterGAP 2 is to provide a basis for both an assessment of current water resources and water use and an integrated perspective of the impacts of global change on the water sector. The WaterGAP 2 model comprises two main components: a Global Hydrology model and a Global Water Use model.

The Global Hydrology model simulates the characteristic macroscale behaviour of the terrestrial water cycle to estimate water availability; in this context "water availability" is defined as the total river discharge, which is the combined surface runoff and groundwater recharge. In a standard global run, the discharge of approximately 10 500 rivers is computed.

The Global Water Use model consists of three main sub-models which compute water use for the domestic, industry, and irrigation sectors in 150 countries. Both water availability and water use computations cover the entire land surface of the globe, except Antarctica (spatial resolution 0.5°, i.e. 66896 grid cells). A global drainage direction map with a 0.5° spatial resolution allows for drainage basins to be chosen flexibly; this permits the analysis of the water resources situation in all large drainage basins worldwide.

Details about the model are given in Alcamo *et al.* (2003).

APPLICATION TO ASSESSMENT OF CURRENT SITUATION

It is, of course, not a straightforward task to assess the current situation of world water resources. Many choices must be made for the assessment; for example, the choice of indicators, and their temporal and spatial resolution. For the assessments in this paper, two indicators are used that encompass many different aspects of water-related issues, and which can be estimated worldwide on the river basin level (see Alcamo *et al.*, 2003), namely water withdrawals and water availability. ("Water availability" is used interchangeably with "discharge", and "annual renewable water resources" within a river basin.) The "current" situation for water withdrawals is represented by the year 1995 because this is the latest year with comprehensive global water-use data. The current situation for water availability is represented by its long-term annual average value over the "climate normal" period (1961–1990).

For domestic and industry withdrawals, country data from Shiklomanov (2000) are allocated to river basins using the algorithms in the domestic and industry water use models explained in the Appendix of Alcamo *et al*. (2003). For agriculture withdrawals, three main sources of information are input to the model: the density of livestock (GlobalARC, 1996), the extent of irrigated land (Döll & Siebert, 2000), and time series of monthly climate data from the climate normal period (1961–1990) (New *et al*., 2000).

For computing water availability (resulting discharge from river basin), monthly climate data from the climate-normal period (1961–1990) are also used (New *et al*., 2000). The advantage of using the WaterGAP 2 model, rather than measurements, to estimate the long-term water availability, is that the model provides a consistent basis for calculating discharge in river basins with incomplete measurements. First, the model can be calibrated to any existing long-term runoff records, even if these data cover only part of the climate normal period. Then, the calibrated model can be run with the appropriate historical climate data to compute average climate normal discharge for every river basin. Therefore the model can be used to compute the water availability covering an identical and standard averaging period for every river basin in the world. The obvious disadvantage of this approach is the unavoidable uncertainty of model estimates discussed in Alcamo *et al.* (2000) and below.

To obtain an overview of the world water situation, the ratio of withdrawals to availability (w.t.a.) is examined. The w.t.a. ratio is a conventional indicator of "water stress" which is a measure of the amount of pressure put on water resources and aquatic ecosystems by the users of these resources, including municipalities, industries, power plants and agricultural users (see, for example, Alcamo *et al*., 2000; Vörösmarty *et al*., 2000; Cosgrove & Rijsberman, 2000; Raskin *et al.*, 1997). Roughly speaking, the higher the w.t.a. ratio, the more often the water in a basin is used and the more it is degraded or depleted, therefore limiting further use of these water resources to downstream users. This indicator has the advantage of being transparent and computable for all river basins.

Figure 1 depicts the withdrawals to availability (w.t.a.) ratio for withdrawals in 1995 and average availability during the climate normal period. The highest w.t.a. values occur, as expected, in arid areas, but also in more humid areas such as the Don, Hudson, Severn, Thames, and most of Florida, because of high water withdrawals. According to this analysis, about 24% of world river basin area (excluding the ice caps) has a w.t.a. ratio of greater than 0.4. This threshold was used by a consortium of United Nations organizations (Raskin *et al.*, 1997), by the World Water Council (Alcamo *et al*., 2000; Cosgrove & Rijsberman, 2000), and by Vörösmarty *et al*. (2000) as an approximate threshold of "high" or "severe" water stress. It is based on expert

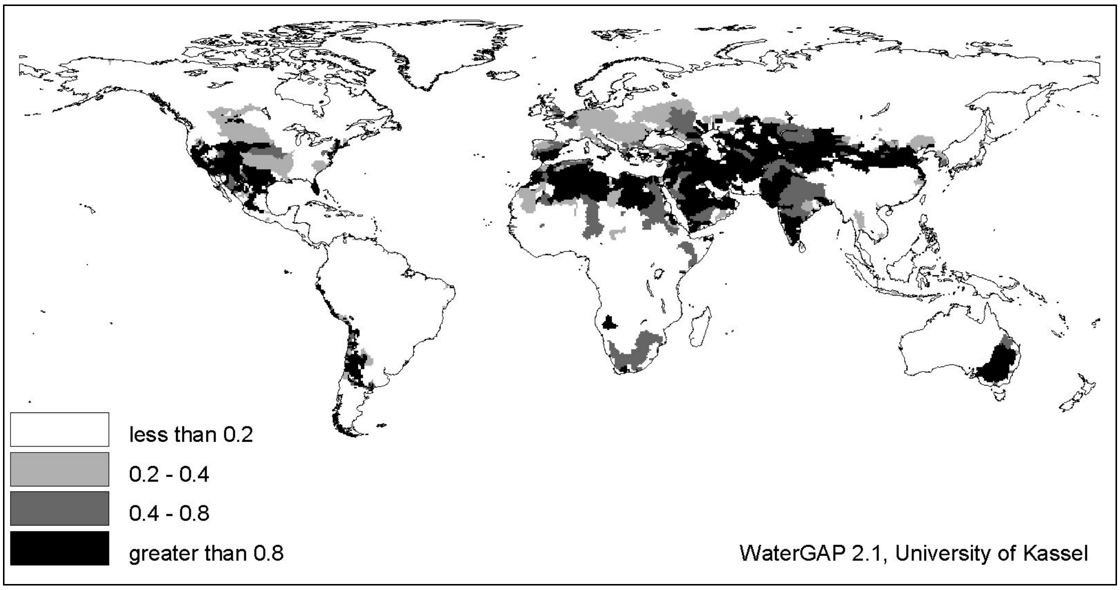

Fig. 1 Withdrawal to availability ratio in 1995 (water availability based on climate normal period, 1961–1990).

judgement and indicates heavy competition between water users. Areas in this category include most of India, northern China, middle Asia, the Middle East, northern and southern Africa, parts of southern Europe, western Latin America, a large part of the western United States, northern Mexico, and a few river basins in Australia. Overlaying these areas with the previously mentioned population density database (van Woerden *et al*., 1995), produces an estimate of 2.1 billion people worldwide living in river basins under severe water stress. This is an intermediate estimate between the 1.7 billion from Vörösmarty *et al.* (2000) and the 2.5 billion from Alcamo *et al.* (1997). The estimate of Vörösmarty *et al.* (2000) is derived by dividing the water withdrawals within each cell by the cell discharge, rather than taking into account upstream withdrawals, as is done in this paper. The estimate of Alcamo *et al.* (1997) refers to areas of "water scarcity" according to an indicator that combines the w.t.a. ratio with water availability per person in river basins.

However, the effects of severe stress are expected to be different in industrialized and developing countries. In industrialized countries, water is intensively recycled by industry, and wastewater is usually treated before being sent on to downstream users. For these and other reasons, industrialized countries can often intensively utilize their water resources without experiencing scarcity. In contrast, in most developing countries, the level of water recycling and wastewater treatment is much lower and so the intensive use of available water resources can cause severe degradation in quality and lead to heavy competition between water users (e.g. periodic disruptions in municipal or industry water supply). Nevertheless, in both developing and industrialized countries, a level of severe stress indicates the likelihood of strong competition for water resources during dry years between municipalities, industry and agriculture.

Since the threshold of w.t.a. of 0.4 is very approximate, a sensitivity analysis was carried out in which this value was varied ±50%. For the 1995 situation, this results in a range of 19–30% of world river basin area under severe stress. In the authors' view, this indicates that conclusions based on a threshold of w.t.a. ratio at 0.4 are fairly robust.

APPLICATION TO A BUSINESS-AS-USUAL SCENARIO FOR 2025

In a second application of WaterGAP 2, the model was used to compute a "business-as-usual" scenario of water withdrawals in 2025 under the assumption that current trends in population, economy and technology continue. Withdrawals in 2025 are then compared with estimates of current water availability from the previous example. In this analysis the possible effects of climate change on water availability or use are not taken into account. Assumptions about the driving forces of this scenario are taken from the business-as-usual scenario (BAU) of the World Water Commission (Cosgrove & Rijsberman, 2000) and are summarized in Table 1. Although this is a reference scenario, trends are not simply extrapolated. Instead, population and economies continue to grow, but at a slower pace. The efficiency of water use continues to improve each year in the domestic and industry water sectors, but also at a slower rate, declining from around 2% year^{-1} to 1% year^{-1} after 2005. Irrigated area expands globally by 1.5% (and only in India, Brazil, and Turkey), and irrigation efficiencies improve at a rate of 0.3% year^{-1}. It is emphasized that this is only one of many possible sets of plausible assumptions for a business-as-usual scenario.

Results for the scenario are grouped into three categories in Fig. 2.

River basins marked white show a stabilization or decrease in water withdrawals between 1995 and 2025 (i.e. increase of no more than 5% compared to the 1995 situation, or 10^6 m^3 km^{-2}). A total of 41% of world river basin area falls into this category. Most river basins in industrialized countries are in this category because water demands tend to saturate in their domestic and industry sectors (see Alcamo *et al.*, 2003, for an explanation of the dynamics of water use in the domestic sector as repre

Table 1 Basic assumptions (Cosgrove & Rijsberman, 2000) and main WaterGAP 2 results for the business-as-usual scenario 2025.

Region	Population in 2025 (1000)	Annual change in GDP cap^{-1} (1995–2025) (%)	Annual change in elec. prod. (1995–2025) (%)	Total change in irrigated area (1995–2025) (%)	Total water withdrawals in 1995 (10^9 m^3)	Total water withdrawals in 2025 (10^9 m^3)
North America	373 344	2.10	1.16	0	533.3	514.5
Central America	230 994	1.77	4.48	0	125.9	171.2
South America	451 678	1.95	4.04	2.2	156.8	207.6
Western Europe	466 614	2.10	0.83	1.8	289.8	269.1
Eastern Europe	127 983	1.89	1.46	0	85.2	89.7
C.I.S.	211 267	2.15	1.92	0	120.2	140.6
Aral Sea basin	78 915	2.17	3.77	0	154.3	162.5
Middle East	363 966	1.40	4.17	0	197.9	206.0
North Africa	261 631	2.06	4.94	0	97.9	114.2
East Africa	386 594	1.83	10.31	0	33.6	46.5
Western Africa	442 464	1.96	8.21	0	13.2	30.7
Central Africa	163 023	1.92	7.72	0	1.9	5.9
Southern Africa	203 158	1.69	4.31	0	20.4	28.1
Australia	32 281	2.05	1.83	0	26.5	26.8
Japan (only)	121 066	0.96	0.76	0	89.1	77.9
China +	1 641 460	4.20	3.57	0	610.9	813.0
South Asia	1 843 800	3.49	5.06	4.8	832.3	951.6
Southeast Asia	628 385	2.98	4.41	0	182.9	235.7
World	**8 028 630**	**-**	**-**	**1.5**	**3572.2**	**4091.5**

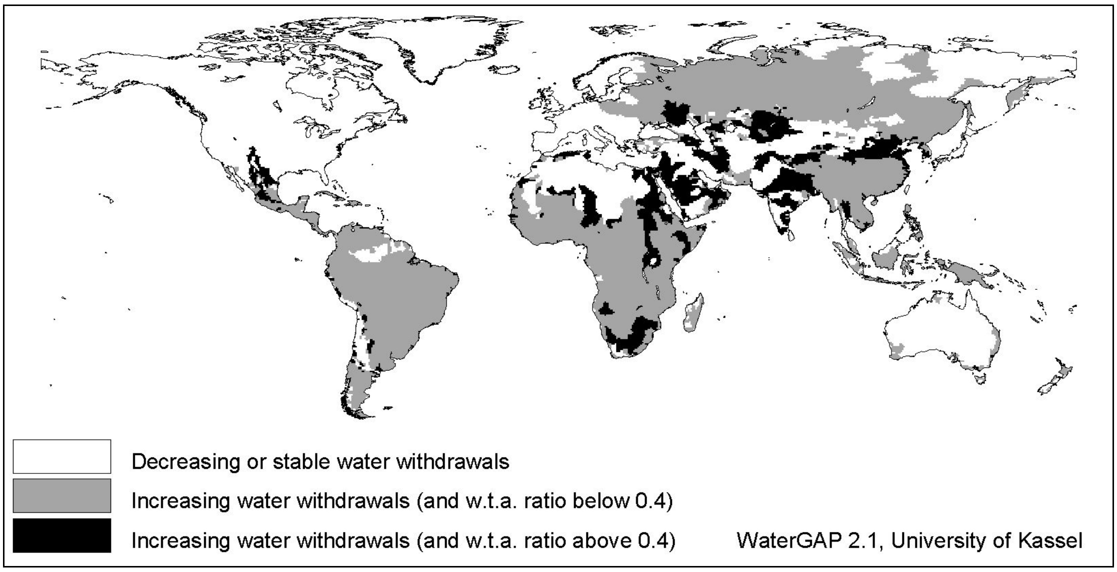

Fig. 2 Water situation in 2025 under a business-as-usual scenario (neglecting climate change).

sented in the WaterGAP 2 model). In addition, the extent of irrigated land stagnates in most countries, and water efficiency improves in all sectors. A decrease in withdrawals may also indicate a decrease in pressure on water resources, especially if the water availability of a basin does not decline because of climate change or other changes in the basin. Nevertheless, a decrease in pressure on water resources does not necessarily mean an improvement in water quality or lessening of the pressure on aquatic ecosystems. Another important point is that, although agricultural water use only grows in a few countries according to this scenario, it still accounts for 56% of global withdrawals in 2025 (compared to 67% in 1995).

River basins marked black are river basins with an increase in water withdrawals, where the pressure on water resources is high under the business-as-usual scenario (as indicated by a w.t.a. ratio greater than 0.4 in 2025). This category includes the Ganges, Huang Ho (Yellow River), Limpopo, and Nile. The growth of withdrawals is influenced by different factors in these basins: population growth leads to large increases in the domestic sector in the Limpopo and Nile basins; the industry sector of the Nile also rapidly grows because of growth in electricity production; in the Huang Ho basin, economic growth is the primary cause of large increases in water withdrawals in the domestic sector. It is noteworthy that withdrawals increase substantially in these regions despite assumed improvements in water use efficiency noted above. Apparently the pressures of population and economic growth outweigh the effects of higher water use efficiency.

River basins marked grey indicate areas where withdrawals increase but where the w.t.a. ratio stays below 0.4. As in the previous category, withdrawals grow because of population and economic growth, and despite the improvement in the efficiency of water use. Here pressure on water resources also increases, but the available water is not used as intensively as in the preceding category. Prominent river basins in this category are the Amazon, Congo, Volga and Yangtze.

ESTIMATION OF GEOGRAPHIC VARIATION IN UNCERTAINTY OF WATERGAP 2

In order to assess the preceding estimates it is important to appreciate the types and magnitude of uncertainties that influence model calculations. These include inexact estimates of model parameters (such as the coefficients used to describe evapotranspiration or structural changes in water intensity), errors in model inputs (such as population or precipitation data), or the simplifications of social and natural processes in the form of model equations. To estimate and quantify these and other individual uncertainties is outside the scope of this paper. Nevertheless, a first estimate of the geographical variation in uncertainty of calculations is made, based on the "goodness-of-fit" of the model to observed historical data, or other criteria explained below. A river basin or region is given a score of 1 for a lower level of uncertainty and 2 for a higher level. It needs to be reiterated, however, that this analysis cannot substitute for a full quantitative evaluation of the important individual sources of uncertainties.

Figure 3 presents results for the different component models of WaterGAP 2. Results for domestic and industry water withdrawals are presented in Fig. 3(a) and (b), in which uncertainty is ranked according to the goodness of the fit of the structural change model to the historical trend in regional water intensity (a region receives a ranking of 1 if the r^2 of this fit is above 0.6). Countries fall into the more uncertain category either because their data are more unreliable, or because the simple structural model does not explain the historical trend of their water intensity. In any event, more detailed and accurate data are needed to improve the model and reduce the uncertainty of these calculations.

Figure 3(c) shows results for irrigation water withdrawals, and takes into account that a very important source of uncertainty is the estimate of the extent of irrigated land

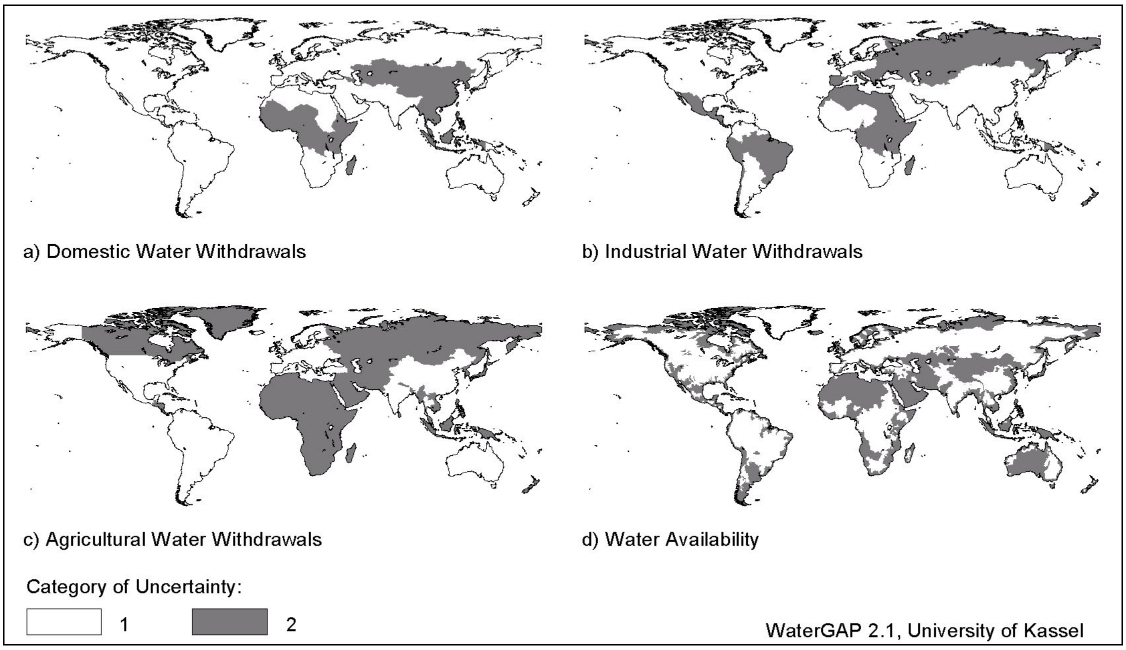

Fig. 3 Geographic variation of uncertainty. Note that the uncertainty of river basins in category 1 is lower than those in category 2.

within a river basin. Here, a river basin is given an uncertainty ranking of 2 if the estimate of irrigated land is based on very approximate information from either maps of irrigated areas, or FAO country data on irrigated areas (see the previous discussion of the irrigation model); it is given a ranking of 1 if it is based on more detailed information (see Döll & Siebert, 2000). Because detailed irrigation data are available for many developing countries, the map of uncertainty for the irrigation calculations has very different patterns from the maps of domestic and industry water use.

Finally, Fig. 3(d) presents results for the Hydrology model, in which a river basin receives an uncertainty ranking of 1 if sufficient discharge measurements were available for calibration of runoff (Case 1 in the section on validation of Alcamo *et al*., 2003) and 2 otherwise. About 50% of world river basin area has sufficient data for calibration.

It is noted that some river basins have a ranking of 1 for all types of calculations and may therefore have somewhat more reliable calculations than the river basins that receive a ranking of 2 for all calculations. However, this conclusion is based on the narrow definition of model uncertainty used in this section. Those with a ranking of 1 in all categories include the river basins of the Mississippi/Missouri and Colorado in the USA, the Godavari, Krishna, and most of the Ganges in India, and most of the Orinoco in Venezuela. Those with a ranking of 2 include many parts of central Asia and large parts of Africa.

DISCUSSION AND CONCLUSIONS

How should the quantitative results presented herein be interpreted? It was shown in the preceding section that the level of uncertainty is likely to vary geographically, and this should be taken into account in assessing results. In Alcamo *et al.* (2003) other conclusions about model calibration and testing are presented. Based on this information, it is believed that the WaterGAP 2 model is suitable for giving an overview rather than specific details about a water resource issue. For example, it is not advisable to use model results for developing a water management plan for a particular river basin. Instead, it is more appropriate to use these results to judge the number and location of basins that are more likely to be under pressure from water use than others. A first estimate of the most affected basins is marked black in Fig. 1, and this shows that a large number of basins (about one-quarter of the area of all river basins) fall into this category. If desert areas are subtracted out, it can still be estimated that about 16% of the total area of all basins are under severe water stress (that is, if a w.t.a. ratio of 0.4 is accepted as an approximate threshold of severe water stress). These are the basins that should be given special attention in the analysis of water scarcity. But it is also necessary to take into account that developing countries are likely to be more sensitive to this stress than industrialized countries.

Also of interest is the longer time perspective afforded by Fig. 2. Rather than a prediction, this figure shows the estimated consequences of the assumed population and other changes in the business-as-usual scenario. One consequence is that withdrawals continue to grow in a large number of river basins where a significant fraction of the annually available water is already withdrawn. These areas are marked black, and make up 12% of the total global area of basins. They could be viewed as “hot spot" problem areas where pressure on water resources is expected to increase, and where the amount of water is more likely (compared to the grey and white areas) to be a limiting factor in economic development.

In other publications of the present authors, the effect of climate change on water use, water availability and water stress is also investigated (Alcamo *et al*., 1997; Alcamo & Henrichs, 2002; Döll *et al.*, 1999; Döll, 2002). As other authors have also found (e.g. Arnell, 1996; Vörösmarty *et al*., 2000), climate changes can significantly increase water stress over a relatively large part of the world, and therefore climate impacts should be included in global water assessments.

In summary, these results point to the growing capability of models of indicating where water resources problems may be more important than others, and where the situation might change dynamically in the future. This top-down approach cannot replace detailed river basin studies, but it can provide a unique global-scale perspective on water resource issues.

Acknowledgements The authors are grateful to Janina Onigkeit, and Eric Kreileman, Joost Knoop, and Hans Renssen of the National Institute of Environment and Public Health (RIVM), The Netherlands, for their contributions to the development of WaterGAP 2. Version 1.0 of WaterGAP 2 benefited greatly from the previous work of Oliver Klepper, also of RIVM.

REFERENCES

Alcamo, J. & Henrichs, T. (2002) Critical regions: a model-based estimation of world water resources sensitive to global changes. *Aquatic Sci*. **64,** 1–11.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. & Siebert, S. (2003) Development and testing of the WaterGAP 2 model of global water use and availability. *Hydrol. Sci. J.* **48**(3), 317–337.

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 no. A9701, Centre for Environmental Systems Research, University of Kassel, Germany.

Alcamo, J., Henrichs, T. & Rösch, T. (2000) World water in 2025—global modeling scenarios for the World Commission on Water for the 21st Century. World Water Series Report no. 2, Centre for Environmental Systems Research, University of Kassel, Germany.

Arnell, N. W. (1996) *Global Warming, River Flows and Water Resources*. Wiley, Chichester, West Sussex, UK.

Arnell, N. W. (1999) A simple water balance model for the simulation of streamflow over a large geographic domain. *J. Hydrol.* **217**, 314–335.

Cosgrove, W. & Rijsberman, F. (2000) *World Water Vision: Making Water Everybody's Business*. World Water Council. Earthscan Publications, London, UK.

Döll, P. (2002) Impact of climate change and variability on irrigation requirements: A global perspective. *Climatic Change* **54**(3), 269–293.

Döll, P. & Siebert, S. (2000) A digital global map of irrigated areas. *ICID J.* **49**(2), 55–66.

Döll, P., Kaspar, F. & Alcamo, J. (1999) Computation of global water availability and water use at the scale of large drainage basins. *Math. Geol.* **4**, 115–122.

GlobalARC GIS Database (1996) Rutgers University and US Army Center for Remote Sensing, US Army Corps of Engineers. http://www.crssa.rutgers.edu/projects/global/

New, M., Hulme, M. & Jones, P. D (2000) Representing twentieth century space-time climate variability: Part II: Development of 1901–96 monthly grids of terrestrial surface climate. *J. Climate* **13**, 2217–2238.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G. & Strzepek, K. (1997) Water futures: assessment of long-range patterns and problems. Comprehensive assessment of the freshwater resources of the world. Stockholm Environment Institute, Stockholm, Sweden.

Shiklomanov, I. (2000) Appraisal and assessment of world water resources. *Water Int.* **25**, 11–32. (Supplemented by CD-ROM: Shiklomanov, I. *World Freshwater Resources*, available from: International Hydrological Programme, UNESCO, Paris, France).

van Woerden, J., Diedericks, J. & Klein-Goldewjik, K. (1995) Data management in support of integrated environmental assessment and modelling at RIVM—including the 1995 RIVM Catalogue of International Data Sets. RIVM Report no. 402001006, National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

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

Received 13 December 2001; accepted 27 January 2003