Aquat. Sci. 64 (2002) 352–362
1015-1621/02/040352-11

Aquatic Sciences

Water Policy Article

Critical regions: A model-based estimation of world water resources sensitive to global changes

Joseph Alcamo* and Thomas Henrichs

Center for Environmental Systems Research, University of Kassel, Kurt-Wolters-Strasse 3, D-34109, Kassel, Germany

Received: 24 May 2002; revised manuscript accepted: 6 September 2002

Abstract. This paper presents a top-down approach for identifying regions whose water resources have higher sensitivity to global change than other regions. The aim of this approach is to provide an overview of regions that may justify special attention from the research and development assistance community, under particular global change scenarios. As a 'top-down' method it is best seen as a type of sensitivity analysis that can complement rather than replace other 'bottom-up' studies of the vulnerability of particular watersheds. An increase in 'water stress' is used as a measure of increasing sensitivity of watersheds to global change, and this stress is computed with the global water model, WaterGAP. Stress increases when either water withdrawals increase or water availability decreases. Since the criteria for determining critical regions is uncertain, they are calculated and compared for four different sets of criteria. To examine the difference in critical regions under different socio-economic and climate scenarios, they were also calculated for four distinctive scenarios. Under the scenario showing the largest increase in water stresses, the estimated area of critical regions (in 2032) ranges from 7.4 to 13.0 percent of total land area, depending on the criteria for identifying critical regions. As expected, the estimate of critical regions is very scenario-dependent, showing smaller areas under scenarios having smaller increases in water stress. However, some regions always appear as critical regions regardless of the scenario. These include parts of central Mexico, the Middle East, large parts of the Indian sub-continent, and stretches of the North African coast.

Key words. Critical regions; global change; global water model; hot spot areas; water scarcity; water stress.

Introduction

Results of research and assessments have shown that water resources world-wide are experiencing large-scale changes in water withdrawals and availability (see, for example, reviews in WWC, 2000 and IPCC, 2001). Using current terminology, these can be termed as 'global changes' owing to their universal nature and their link to global processes. An important research question is, which regions are likely to be most affected by global changes and therefore deserve special attention for monitoring and research? Likewise, many policymakers and development assistance institutions are interested in mitigating the negative impacts of global changes, but may have limited resources for this task. They also are interested in where development aid can be best concentrated. For these reasons it would be useful to identify 'critical regions' where water resources might be especially sensitive. These regions could then be given priority for further monitoring, research or mitigation efforts.

Previous studies, for example the 'Comprehensive Assessment of Freshwater Resources of the World' supported by a Consortium of U.N. organizations, signaled increasing water vulnerabilities for several countries (Raskin et al., 1997). Also, a country-based scenario-analysis by the International Water Management Institute

---

* Corresponding author fax: +49 561 804 7266;
e-mail: alcamo@usf.uni-kassel.de

highlighted countries with either high levels of water stress today or high increases in water demand or both (IWMI, 1998). But while country-scale assessments provide an useful first overview, it is widely agreed that analyses of water resources would ideally be conducted at the watershed-level. Recent global assessments of the stress on water resources at the watershed-level have shown that around 2 billion people live in watersheds with high water stress today, and that this number likely to increase considerably (for example, Alcamo et al., 1997; Alcamo et al., 2000; Cosgrove and Rijsberman, 2000; Vörösmarty et al., 2000; World Resources Institute, 2000). These studies identified regions that see particular high stress on water resources either today or under various future scenarios, yet they do not take the rates of changes or the increase of pressure on water resources into account explicitly. With this study we aim to take the analysis one step further, by assessing which regions have critical sensitivity to the dynamics of global changes.

The objective of this paper is to present and apply a model-based, top-down approach for identifying 'critical regions'. We stress at the outset that such a top-down approach can complement but not replace detailed bottom-up vulnerability studies of particular watersheds. For instance, the top-down approach can be viewed as a kind of screening analysis to determine where bottom-up assessments of vulnerabilities should be carried out. Furthermore, the top-down approach can address questions that are difficult (or currently impossible) for bottom-up case studies to address. For example:

1. Which regions of the world might be most affected by global change under different criteria for 'critical region'?
2. Which regions are critical under a range of different global change scenarios?
3. What will be the impacts of global change on regions where watershed-level studies up to now are limited or absent?
4. Do critical regions for water resources coincide with critical regions for other types of global change impacts, for example areas where impacts on natural vegetation or crop production are particularly important?

Defining critical regions

The general definition of 'critical region' used in this paper is: 'A region whose water resources have higher sensitivity to global change than other regions.' 'Region' is used to mean a broad geographical area, while 'global change' refers to alterations in natural (e.g., physical or biological) systems whose impacts are not localized (Stern et al., 1992). These changes can be systemic (e.g., ozone depletion, climate change) or cumulative (e.g., deforestation, shifting settlements, water scarcity). With regards to water resources, global changes fall into both the systemic (as in changes in the global climate system which lead to changes in precipitation patterns and runoff) and cumulative categories (e.g., water consumption increasing simultaneously in many watersheds leading to more frequent water shortages at many different locations around the world). Here we consider the following water resource processes as global changes: (i) The change in water withdrawals owing to changes in population, economic growth, and technological change, (ii) Changes in water availability (equivalent to the natural discharge in each watershed) due to long term, average changes in precipitation and temperature due to climate change.[1]

'Sensitivity' in the above definition is used in the conventional sense as the degree of change of a dependent variable relative to change of an independent variable. In this analysis, sensitivity is the change in water resources per unit 'global change'. The question arises, what kind of changes to water resources should be taken into account? The answer depends on the viewpoint towards water resources – Different kinds of changes will be important to aquatic ecosystems, to local municipal or industrial users, to ships navigating a river, and so on. In this paper we do not attempt to address a particular perspective, but instead use a general measure of sensitivity which we believe is relevant to a number of different interests in water resources, namely, the change in water stress. 'Water stress', as used here, is a measure of the degree of pressure put on water resources (including its quantity and ecosystems) by the users of these resources, including municipalities, industries, power plants and agricultural users. For the purpose of this analysis, it is assumed that the greater the increase in water stress, the greater the sensitivity of water resources to global change.[2]

To estimate water stress we use the common indicator 'annual withdrawals-to-availability ratio' (see, e.g., Raskin et al., 1997; Cosgrove and Rijsberman, 2000).[3] Figure 1 depicts the current situation of water stress in the world's watersheds. Water stress will increase when either water withdrawals grow (related to changes in population

---

[1] As a first approach, we only take into account average annual changes, but in future analyses we intend to include changes in the frequency and intensity of extreme climate events.

[2] We are concerned with an increase rather than decrease of stress because the aim of this paper is to identify regions experiencing negative impacts of global change.

[3] Based on this indicator, water stress can be divided into 'low', 'medium' and 'severe' classes using conventional thresholds. When the long-term average annual withdrawals to availability ratio is …
– … greater than 0.4, then water stress is 'severe';
– … between 0.2 and 0.4, then water stress is 'medium';
– … less than 0.2, then water stress is 'low'.

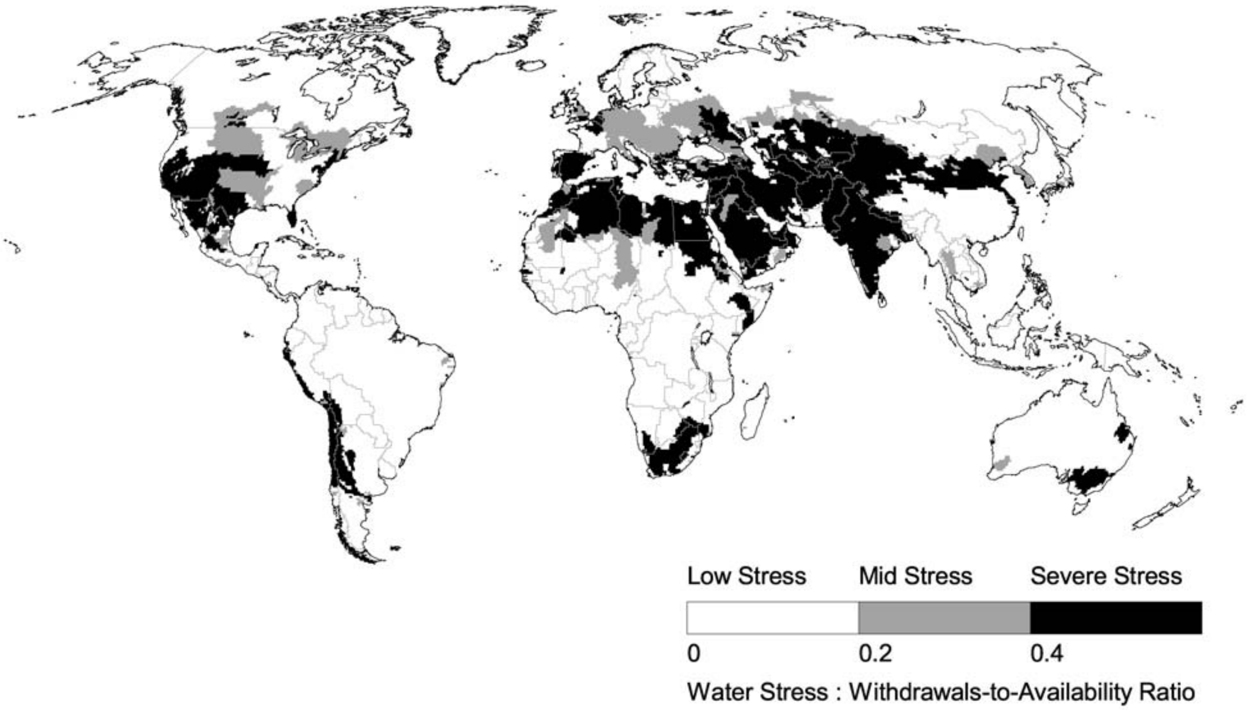

Figure 1. Current water stress: Water stress is depicted by the current average annual withdrawals-to-availability ratio as computed by the WaterGAP model (Alcamo et al., 2002). Water withdrawals are representative for the situation in 1995, computations of water availability are based on the climate normal period 1961–1990.

and economic growth), and/or water availability decreases (related to climate change). Water stress will remain at the same level if the proportional increase/decrease in withdrawals is the same as the proportional increase/decrease in water availability.

To sum up to this point, a general definition for critical regions has been proposed, and it is interpreted specifically here to mean regions experiencing an increase in water stress on the watershed-level because of either increasing water withdrawals or decreasing water availability related to global change processes. One more question must be addressed before we can compute critical regions – How much must water stress increase before regions become critical regions? Since there is no single best answer to this question, we compare the critical regions computed under four different sets of criteria (Table 1).

Criteria Set #1 is relatively easy to interpret since it specifies that critical regions are those areas already under severe water stress and experiencing any increase in stress. This avoids the difficult task of assuming a threshold for the rate of increase of water stress. At the same time it has the disadvantage of implying that every and any increase in water stress is significant, no matter how small.

In Criteria Set #2, the conditions for critical regions are made more stringent by requiring that water stress must increase by at least one percent per year. The assumption here is that society and ecosystems can adapt to a rate of increase of water stress of up to one percent per year without disruption. An example of a measure to adapt to water stress would be, for example, to increase the level of wastewater treatment in a watershed in order to increase the overall quality of freshwater for human

Table 1. Criteria for critical regions.

Criteria Set #1.
1. Watersheds must currently be under ‘severe water stress’ [a] ; and
2. The increase in water stress because of global change must be greater than zero.

Criteria Set #2.
1. Watersheds must currently be under ‘severe water stress’ (same as Definition 1); and
2. Water stress must increase by at least one percent per year because of global change.

Criteria Set #3.
1. Watersheds must currently be under ‘medium water stress’ [b] ; and
2. Water stress must increase by at least one percent per year because of global change (as in Definition 2).

Criteria Set #4.
1. Watersheds must currently be under ‘medium water stress’ (same as Definition 3); and
2. Water stress must increase by at least one percent because of global change (same as Definitions 2 and 3); and
3. Watersheds must be located in countries in the ‘higher susceptibility’ category (as defined in text).

[a] See footnote 3 for definition of severe water stress..
[b] See footnote 3 for definition of medium water stress.

use and aquatic ecosystems. Other measures would be to increase the storage of water, or to transfer water by technical means or economic incentives from remote water-rich parts of a watershed. If the past is any guide, then it seems adaptation rates in excess of one percent are feasible. For example, during the 1970s and 80s, the number of people serviced by wastewater treatment in OECD countries increased by 3.5 or more percent per year.[4] On the other hand, even a one percent annual increase in water stress might be difficult to cope with in poorer countries. Hence, the disadvantage of this set of criteria is the uncertainty of the one percent estimate.

Another drawback to both Criteria Sets #1 and #2 is that they assume that critical regions must currently be in the 'severe water stress' category. In reality, the boundary between 'medium' and 'severe' water stress is poorly known. Hence, in Criteria Set #3, we relax the starting conditions for critical regions from 'severe water stress' to 'medium water stress'.

With Criteria Set #2 we took into account adaptation by assuming a maximum allowable rate of increase of water stress. Another way to account for adaptation is to estimate the overall susceptibility of the local human (and ecosystem) population. But this susceptibility depends on a complex web of technical, social, economic, cultural, and other factors which are difficult to represent globally. Nevertheless we believe that omitting susceptibility altogether from the analysis would represent an even greater error. Therefore in Criteria Set #4 we use the Human-Development Index (HDI) of the United Nations Development Programme (UNDP, 1997) as a proxy variable for relative susceptibility of human populations – The aim of the HDI is to give a broader indication of the state of human well-being than the traditional measure of gross national product (GNP). GNP is nevertheless included as one of HDI's three components, the other two being literacy rate and the rate of infant mortality. For this analysis we divide the world into two categories – (i) Nations with 'lower susceptibility' (having an HDI in 1995 greater or equal to 0.80) which include Argentina, Australia, Canada, the United States, and Western Europe; and (ii) Nations with 'higher susceptibility', made up of the rest of the world. For Criteria Set #4 we use the same requirements as Criteria Set #3 plus the criterion that critical regions must be in a 'higher susceptibility' country (see Table 1, Criteria Set #4).

Calculating critical regions

Method for calculating water stress

Now that we have specified the criteria for critical regions, we can proceed with their calculation. As described above, calculating water stress requires the computation of annual withdrawals and availability on the watershed-level. For these calculations we use the WaterGAP global water model (Alcamo et al., 2002; Döll and Siebert, 2002). WaterGAP computes water withdrawals in the domestic and industrial sectors by relating changes in national income to changes in the amount of water used per person and per unit electricity generated. These calculations also take into account the saturation of water demands at high incomes, and continuing improvements in water use efficiency due to technological change. Water requirements for irrigated crops are computed by taking into account the location of irrigated areas, local climate, and variables relating to crop and cropping characteristics. Water availability (equivalent to the natural stream discharge plus groundwater recharge in each watershed) is computed from daily water balances of the vegetation canopy and soil. These water balance computations are driven by precipitation, temperature, and other climate data. A water balance is also performed for open waters, and river flow is routed through a global flow routing scheme. WaterGAP calculations of withdrawals and availability have been either calibrated or independently tested against existing data sets.

Scenarios analyzed

The magnitude and distribution of future water withdrawals and water availability depend on assumptions about their future driving forces, which include demographic, economic and technological changes, and future patterns of precipitation and temperature. Estimates of these driving forces were taken from four global scenarios recently developed for the Third Global Environmental Outlook report of the United Nations Environment Programme (GEO-3; UNEP, 2002). The GEO-3 scenarios contain grid-scale and regional quantifications of key socio-economic driving forces and of resulting patterns of climate change as provided by a set of different models, including PoleStar (Raskin et al., 1999) and IMAGE (Integrated Model to Assess the Global Environment, version 2.2; Alcamo et al., 1998; RIVM, 2001). An overview of these scenarios is given in Table 2. As part of our analysis here we compare results from 2032 with 'current conditions' (as represented by conditions in 1995).

---

[4] As an example, the number of people served by wastewater treatment increased at an annual rate between 1970 and 1989 of 3.5, 4.1, and 8.8 percent, respectively for North America, OECD Europe, and Japan. (OECD, 1991). There is evidence, however, that these rates have slowed over the last decade.

Table 2. Overview of scenarios.

"The 'Markets First' scenario envisages a world in which market-driven developments converge on the values and expectations that prevail in industrialized countries" (UNEP, 2002). Under the assumptions made for this paper world population increases from the current 6 billion to 8.2 billion in 2032, global electricity production is more than 2.5 times higher than today, income annually grows by 2.3 percent on the average (ranging from less than 2 percent in today's industrialized countries to more than 4% in Eastern Europe or Southern Asia). At the same time, carbon dioxide emission increase significantly over the next thirty years, and result in an atmospheric concentration of carbon dioxide of 450 ppm; this leads to an on-going increase in global temperature change from 0.2 °C per decade today to 0.3 °C per decade in the 2030 s. The area of irrigated land expands globally by more than 20% (especially in Southern and Eastern Asia; following the Technology-Economy-Private Sector scenario of the World Water Vision (Cosgrove and Rijsberman, 2002, Alcamo et al., 2000). Technological change continues to improve the efficiency of water use at rates somewhat lower than historical rates. Computed with the WaterGAP model, these assumptions lead to an increase in water withdrawals world-wide from 3.500 km^3 in 1995 to 4900 km^3 by 2032.

"In a 'Policy First' scenario, strong actions are undertaken by governments in an attempt to reach specific environmental and social goals" (UNEP, 2002). World population grows to 8.2 billion and income growth is higher than under 'Markets First'. The income gap between industrialized and developing countries is closed somewhat. Despite reductions in carbon dioxide emissions through carbon taxes and investments into non-fossil-fuel energy sources, atmospheric concentrations of carbon dioxide still rise to over 400 ppm; and thus global temperature change remains at around 0.2 °C to 0.25 °C per decade. Meanwhile policy adjustments lead to significant structural changes in water use and to greater water saving compared to historical trends. The global extent of irrigated area adjusts better to actual water availability in different regions by shifting to less arid regions (in total leading to a global increase in the extent of irrigated areas by about 5% following the Values and Lifestyles scenario of the World Water Vision). Computed with the WaterGAP model, these assumptions lead to a reduction in water withdrawals world-wide to 2800 km^3 by 2032.

"The 'Security First' scenario assumes a world of great disparities, where inequality and conflict prevail, brought about by socio-economic and environmental stresses" (UNEP, 2002). This scenario has the highest increase in world population (9 billion people in 2032). Global average annual income growth (1.5 %) is somewhat lower than the other scenarios. The effects of lower economic growth pushes down per capita energy consumption and slower emissions growth; still global temperature still rises at 0.2 °C per decade. Irrigated areas remain at their current extent (following more or less the Business as Usual scenario of the World Water Vision). Computed with the WaterGAP model, these assumptions lead to an increase in water withdrawals world-wide to 4200 km^3 by 2032.

" 'Sustainability First' pictures a world in which a new development paradigm emerges in response to the challenge of sustainability, supported by new, more equitable values and institutions" (UNEP, 2002). While assumptions on world population are the same as under 'Markets First', income growth is markedly higher in developing countries. Dramatic behavioral shifts in conjunction with significantly improved conversion efficiencies result in a very rapid leveling off of emissions; due to the time lags in the climate system global temperature still rises at 0.2 °C to 0.25 °C per decade in the next thirty years. The extent of irrigated area is altered as under 'Policy First', leading to a shift to less arid dry regions (again following the Values and Lifestyles scenario of the World Water Vision). Also policy adjustments lead to a marked structural changes in water use, and at the same time technological change continues to improve water use efficiency at historical rates. Computed with the WaterGAP model, these assumptions lead to an reduction in water withdrawals world-wide to 2700 km^3 by 2032.

Results

Using the above described four sets of criteria and four scenarios we carried out two distinct analyses of critical regions. First, we use one scenario to examine the sensitivity of critical regions to the four different sets of criteria. In the second analysis we hold the criteria constant, and investigate the sensitivity of critical regions to the four different scenarios.

For the first analysis we use the Markets First scenario because it has the largest changes in water withdrawals and availability. Figure 2 presents the estimation of critical regions according to this scenario and the four sets of criteria. Table 3 summarizes the area of each continent in the critical region category. According to Criteria Set #1, (Fig. 2 a), critical regions include the following areas: in North America – the northern region of Mexico and a small part of the southern United States; in Latin America – a small part of its west coast; in Europe – the lower Seine and Rhine, and the lower Don and Volga; in Africa – a large section of South Africa, a part of the Northwest of the continent, and the Nile basin; in Asia – much of the Middle East, northern China, and most of India and Pakistan; in Australia – the Murray-Darling Basin. In total 17.2 million km^2, or 13.0 % of the world's watershed area (outside of Greenland and Antarctica) falls into the critical region category; some 3 billion people are estimated to live in critical regions. This is the largest extent of area or population for any of the sets of criteria (Table 3). Some of areas are critical because of increasing water withdrawals (e.g., the lower Nile, Rio Grande, northern China – a total of 6.7 million km^2), some because of changes in precipitation and temperature that lead to decreasing water availability (e.g., parts of Spain, parts of Argentina, parts of North-West Africa – a total of 1.9 million km^2), and some because of a combination of both (e.g., South Africa, many areas in the Mediterranean, the Near East, most of India, the Don basin, the Murray-Darling basin – a total of 8.7 million km^2).

The criteria for critical regions is somewhat more strict under Criteria Set #2 (water stress must increase by one percent or more per year, or by a total of 45%

Fig. 2a: Criteria Set #1

Fig. 2b: Criteria Set #2

Figure 2. Sensitivity of critical regions to different criteria: Critical regions under 'Markets First' scenario and according to four different criteria for changes in water stress and/or level of susceptibility.

between 1995 and 2032). In this case almost all regions are reduced in size, or drop out altogether (Fig. 2b). In Africa and North America the total area of critical regions is smaller than any of the other sets of criteria (Table 3). In Europe, there are almost no critical regions, whereas under the other sets of criteria the area of critical regions ranges from 6.8 to 9.5 % (Table 3). In Asia, the critical region of North China drops out, but other critical regions remain, although smaller in size. Worldwide, a total of 9.8 million km^2 (i.e., 7.4 %) are in the critical region category with slightly more than 2 billion people living in these regions. These are the lowest estimates of the four sets of criteria.

Under Criteria Set #3, the criteria is widened to include watersheds under medium water stress as well as those under severe water stress. For North America and Latin America the picture of critical regions does not change very much (Fig. 2c). In Europe, however, two new regions appear – the Elbe-Oder and Dnieper-Dniester watersheds. There are no large changes as compared to Criteria Set #2 in Africa, Asia or Australia except for the addition of the Chad inland sea basin in Africa. A world-

Fig. 2c: Criteria Set #3

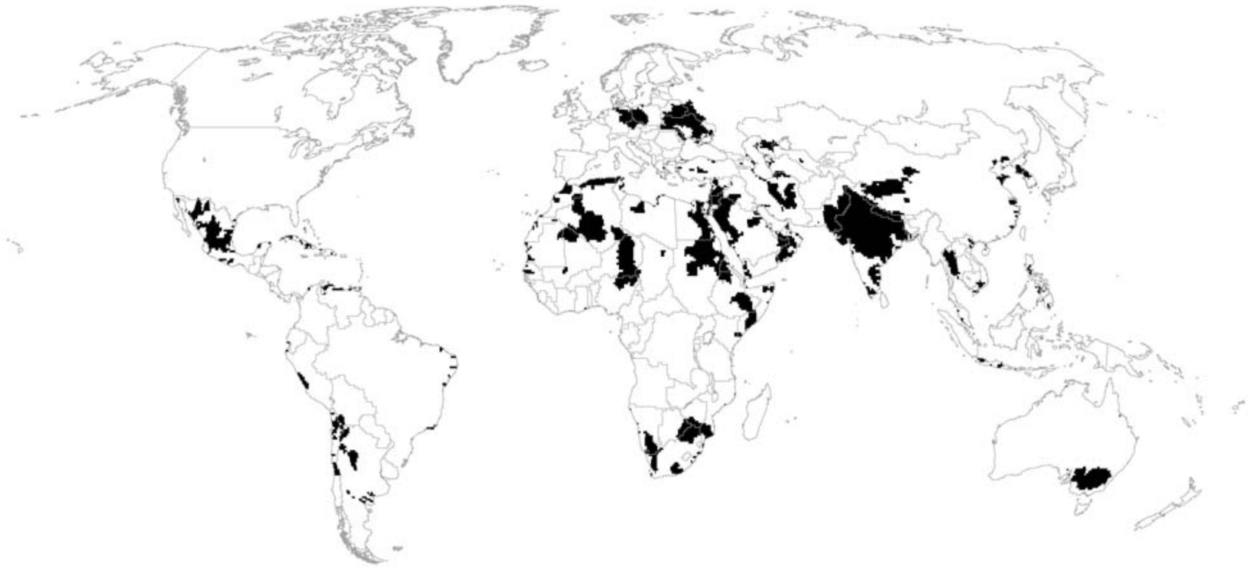

Fig. 2d: Criteria Set #4

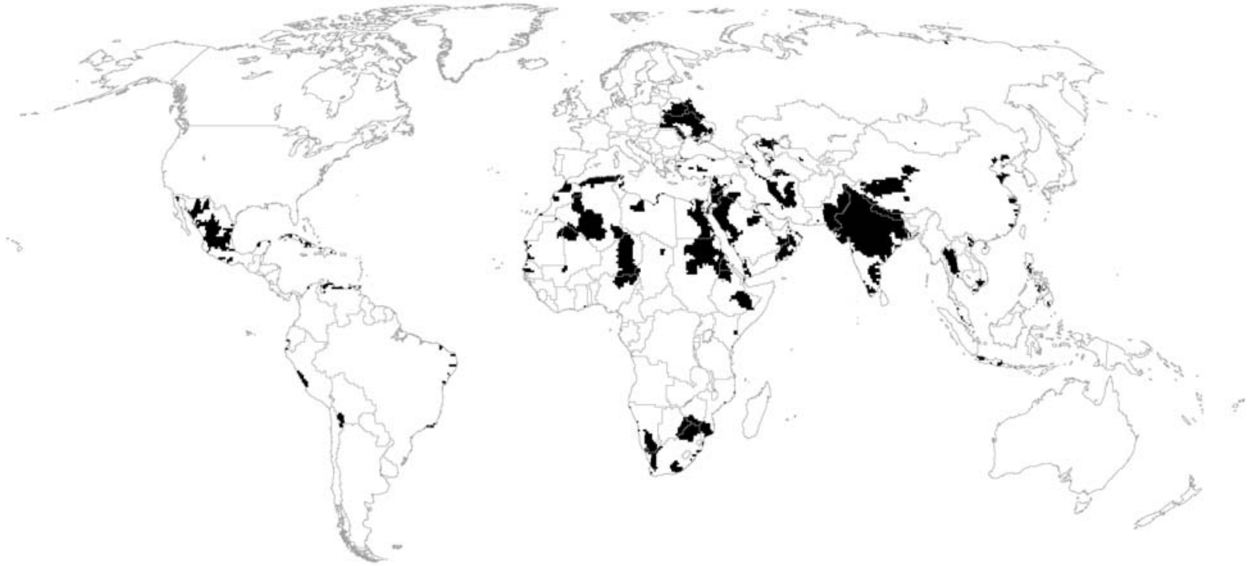

Figure 2 (continued)

wide total of 13.2 million km² (i.e., 10.0 %) are in the critical region category and nearly 2.6 billion people are estimated to live in critical regions.

Criteria Set #4 includes the regions that are critical under Criteria Set #3 and that are in the 'higher susceptibility' category as defined above (Fig. 2d). The critical regions are the same as for Criteria Set #3, except that regions in Argentina, Australia, Germany, and Poland drop out because they are in the 'lower susceptibility' category. Under this set of criteria, Australia and Latin America have the smallest extent of critical regions (Table 3). A worldwide total of 11.7 million km² (i.e., 8.8 %) are in the critical region category, with more than 2.4 billion people living in these regions.

While the estimation of critical regions is indeed dependent on the selected set of criteria, the estimation did not vary very drastically. For the Markets First scenario in 2032, the total computed area of critical regions ranged from 7.4 to 13.0 % of the land area of the world (outside of Greenland and Antarctica), depending on the selected criteria for critical regions. Estimates for Africa and Asia

Fig. 3a: Critical Regions (Markets First Scenario)

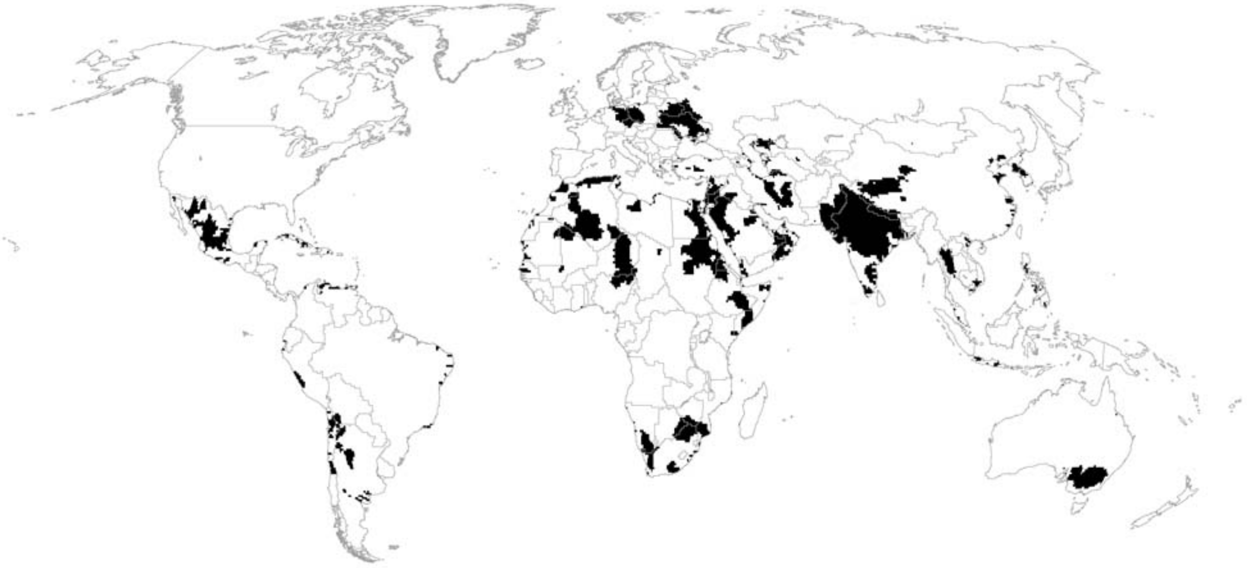

Fig. 3b: Critical Regions (Security First Scenario)

Figure 3. Sensitivity of critical regions to scenarios: Critical regions according to Criteria Set #3, and under four different scenarios.

were also within a factor of two (Table 3). In addition, the core regions remained about the same for all sets of criteria, and included parts of the arid and/or populated western coastline of Latin America, parts of northern and central Mexico, the Middle East, much of India and Pakistan, the Algerian coast, the lower Nile basin, and parts of Eastern and Southern Africa (including the Shebelle and Limpopo basins).

In the second analysis, we hold the set of criteria constant, and compute the dependence of critical regions on the four scenarios in Table 2. For this analysis we use Criteria Set #3 because these criteria gave intermediate global results (Table 3). As expected, the estimation of critical regions is very sensitive to scenario assumptions. The Policy First scenario (Fig. 3c) had the smallest overall increase in water stress and a much smaller area of critical regions (3.8 %; 1.4 billion people) than the Markets First scenario (10.0 %, 2.6 billion people) which had the largest increase in stress (Fig. 3a). This implies that policies that lead to lower withdrawals and increased availability can lead to a smaller extent of critical regions, at least according to the concepts introduced in this paper.

Fig. 3c: Critical Regions (Policy First Scenario)

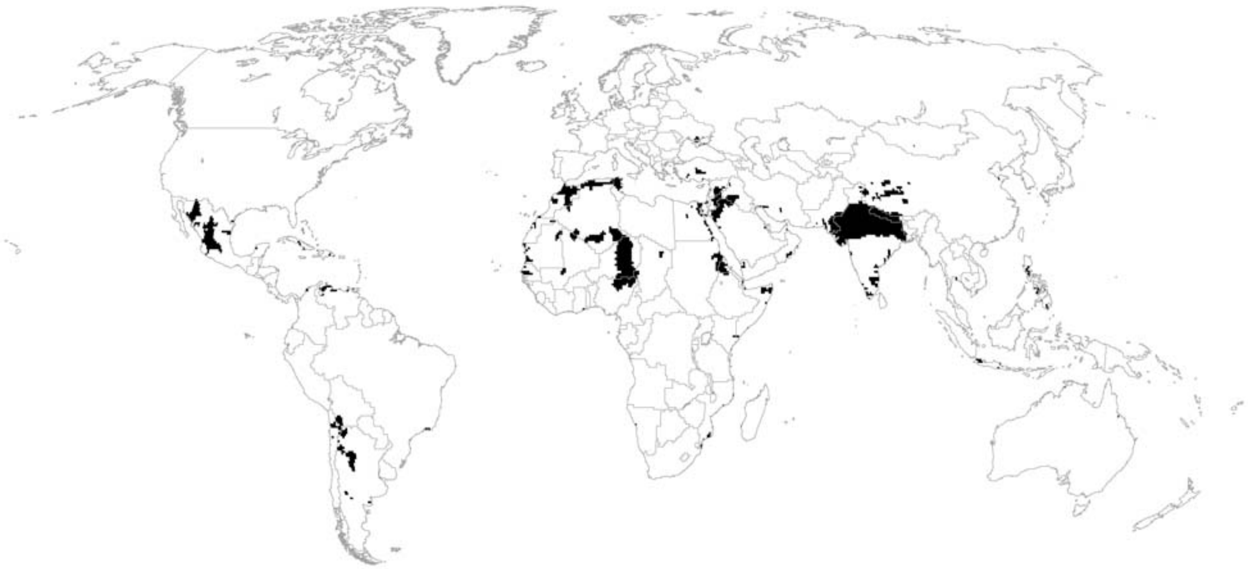

Fig. 3d: Critical Regions (Sustainability First Scenario)

Figure 3 (continued)

The other scenarios had intermediate areas of critical regions – 4.9 % (Sustainability First) and 8.2 % (Security First). The Sustainability First scenario even resulted in a lower population living in critical regions (1.2 billion) than the Policy First scenario, while under the Security First scenario the population in critical regions is of a similar order of magnitude (2.3 billion) as calculated for the Markets First scenario.

Interestingly, some areas appear critical regardless of the scenario. These are a subset of the above mentioned core regions, including small parts of central Mexico, the Middle East, the Ganges-Indus region, the Algerian coast, plus the Chad region (Fig. 3). According to the concept of critical region used in this paper, these areas might have a higher probability of being sensitive to global changes than other regions.

Discussion and conclusions

A few points are especially important to keep in mind when interpreting the results presented in this paper. First

Table 3. *Percentage* of continental areas that fall into critical category according to different sets of criteria under the ‘Markets First’ scenario.

Continent	Criteria Set #			
	1	2	3	4
World	13.0	7.4	10.0	8.8
Africa	17.0	11.0	15.0	14.0
Asia	18.0	11.0	13.0	13.0
Australia	7.5	5.2	5.3	0
Europe	9.2	0.8	9.5	6.8
North America	6.5	2.6	3.8	3.6
Latin America	5.6	2.8	3.6	1.4

of all, the concept of ‘critical regions’ is *relational* in that it compares the condition of one region to another, rather than describes the condition of a particular region independent of others. Indeed, this concept is best viewed as a type of sensitivity analysis for identifying particularly sensitive regions. Thus the approach described in this paper can serve as first screening analysis to identify critical regions that need further vulnerability assessments, and not as a substitute for detailed assessment of global change impacts in a particular region. Conversely, the results of this kind of screening analyses should not be taken to be exclusive: Also regions that this screening analysis does not identify as being critical may still in fact experience significant impacts of global changes.

Another factor to keep in mind is that critical regions are estimated *with respect to global change*, rather than with respect to other factors. Of course, many regions already have water resources that could be considered to be in ‘critical condition’ because they have sustained decades of intensive water use and have slowly degraded or finally reached a breaking point. But the goal here is not to identify regions with currently critical conditions, but rather the subset of these regions whose condition may worsen because of global change. Therefore, some regions where water problems are recognized to be severe today (highlighted in Fig. 1) do not appear as critical regions here (in Figs. 2 or 3).

Also, we remind the reader that the analysis presented here relies on world-wide data-sets and results from global models. These have seen considerable advancements recently, but still entail substantial uncertainties. For example, precipitation projections by climate models still have high uncertainties connected to them, and these are propagated through the hydrology model. While this remains a major source of uncertainty for long-term water availability projections, the developments described in this paper are dominated by the expected changes in water withdrawals for most critical regions. But estimates of water withdrawals also have large uncertainties. In particular, adequate time series data for calibrating the water use model are lacking.

Nevertheless, and taking into account the previous qualifications, an interesting finding of this paper is that estimates of the total area of critical regions in the world vary by less than a factor of two despite the fact that very different sets of criteria were used for the calculations. Some regions appear critical for all criteria sets and scenarios investigated in this paper, hinting that these regions may have a higher likelihood of being critical than other regions. As noted above, these regions include parts of central Mexico, the Middle East, large parts of Indian sub-continent, and stretches of the North African coast. Still, future studies must test the robustness of these calculations against an even larger number of different criteria.

In this paper a set of four different criteria to define ‘critical regions’ has been proposed and applied, yet we realize that an even wider range of criteria sets are equally conceivable. Moreover, applying different criteria sets may well render different regions to be critical. An important example is that the criteria used here are based on long-term annual averages of water withdrawals and water availability, and do not specifically address seasonality, inter-annual variability or frequencies of extreme events. Another point is that although the criteria sets introduced here include a first attempt to take into account means of adaptation to global changes (via the Human-Development Index), the representation of economic, social, political, institutional, and cultural factors can clearly be improved.

Indeed it would be informative to extend the screening analysis in this paper by applying both a wider range of criteria and a larger variety of scenarios, and then compiling the frequency with which regions appear as critical. Results could then be expressed in probabilistic form such as ‘Region X appeared as a critical region in 75 % of the cases’ which better expresses the uncertainty of this approach than the deterministic statements in this paper.[5]

Another important finding is that some watersheds are classified as critical regions under one scenario, and drop out of this category under another (for example many of the African watersheds, including the lower Nile and Southern Africa, are critical regions in a Markets First scenario, but not under a Policy Reform scenario). By this the scenarios highlight possible pathways of future development that may prevent further intensification of water stress or may even lead to considerable improvements of the water resources situation. And thus, besides

---

[5] But care must be taken in interpreting the results of such an analysis as “probabilities”. For example, such an interpretation must take into account that not all scenarios have equal likelihood.

identifying critical regions, this kind of analysis can help in developing strategies of how to adapt to pressing global changes in potentially critical regions.

In closing, although the top-down approach presented herein has unavoidable uncertainty, it nevertheless provides insight into the key question – which regions have water resources especially sensitive to global change? Helping to address this question can provide input to difficult decisions about how to best allocate limited resources for research, monitoring, and development assistance.

Acknowledgments

The authors acknowledge the contributions of Petra Doell, Bernard Lehner, and Frank Kaspar to the calculations presented in this paper. The work presented herein was partly supported by funds from the "Dialogue on Water and Climate".

References

Alcamo, J., P. Döll, F. Kaspar and S. Siebert, 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, Germany.

Alcamo, J., R. Leemans and E. Kreileman (eds.), 1998. Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 Model, Elsevier Science, Oxford, UK.

Alcamo, J., T. Henrichs and T. Rösch, 2000. World water in 2025 – global modeling scenarios for the World Commission on Water for the 21st Century. Kassel World Water Series, Report Number 2, Center for Environmental Systems Research, University of Kassel, Germany.

Alcamo, J., P. Döll, T. Henrichs, B. Lehner, F. Kaspar, T. Rösch and T. Siebert, 2002. WaterGAP: development and application of a global model for water withdrawals and availability. Hydrological Sciences Journal (in press).

Cosgrove, W. and F. Rijsberman, 2002. World Water Vision: Making Water Everybody's Business, Earthscan Publications Limited, London, 108 pp.

Döll, P. and S. Siebert, 2002. Global modeling of irrigation water requirements. Water Resources Research **38(4):** 8.1-8.10.

Intergovernmental Panel on Climate Change (IPCC), 2000. Special Report on Eemission Scenarios, Cambridge University Press, Cambridge, 599 pp.

Intergovernmental Panel on Climate Change (IPCC), 2001. Climate Change 2001 – Impacts, Adaptation, and Vulnerability, Cambridge University Press, Cambridge, 1032 pp.

International Water Management Institute (IWMI), 2000. Water Demand and Supply, 1990 to 2025: Scenarios and Issues.

Raskin, P., P. Gleick, P. Kirshen, G. Pontius and K. Strzepek, 1997. Water futures: Assessment of long-range patterns and problems. Comprehensive Assessment of the Freshwater Resources of the World, Stockholm Environment Institute, Box 2142. S-103 14, Stockholm, Sweden.

Raskin, P., C. Heaps, J. Sieber and E. Kemp-Benedict, 1999. PoleStar System Manual, Polestar Series Report 2, Stockholm Environment Institute, Boston, United States.

Stern, P. C., O. R. Young and D. Druckman (eds.), 1992. Global Environmental Change: Understanding the Human Dimensions, National Academy Press, Washington, 308 pp.

Organization of Economic Cooperation and Development (OECD), 1991. State of the Environment, 1991. OECD, 2 rue Andre-Pascal. 75775 Paris, CEDEX 16, France.

RIVM, 2001. The IMAGE 2.2 implementation of the SRES scenarios: Climate change scenarios resulting from runs with several GCMs. RIVM CD-ROM Publication 481508019. National Institute for Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

United Nations Development Programme (UNDP), 1997. Human Development Report 1997, Oxford University Press.

United Nations Environment Programme (UNEP), 2002. Global Environmental Outlook 3, Earthscan Publications Ltd, London, 404 pp.

Vörösmarty, C. J., P. Green, J. Salisbury and R. B. Lammers, 2000. Global water resources: Vulnerability from climate change and population growth. Science **289**: 284-288.

World Resources Institute (WRI), 2000. World Resources 2000–01, Oxford Press, New York.

World Water Commission (WWC), 2000. World water vision: A water-secure world. World Water Commission Report. Available from UNESCO, Division of Water Sciences, 1 Rue Mollis, F-75015 Paris, France.