STATE AND PERSPECTIVES OF GLOBAL WATER CRITICALITY ESTIMATION

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1 INTRODUCTION

In defining water criticality the dimensions of water scarcity and the availability of coping strategies have to be taken into account. Water scarcity is generated by an unfavourable relation between water demand and water availability. Therefore coping strategies have either to reduce demand or to enhance availability. Water demand can be addressed by efficiency increase of water use in the widest sense (including substitution). Water availability depends on natural circumstances as well as on anthropogenic influences. While the first are determined by climatic zones and topographical properties, the latter have to be divided into direct interventions like water infrastructure and water pollution and, on the other hand, indirect interventions, e.g. via anthropogenic climate change originating from greenhouse gas emissions.
The last point is one aspect why it is reasonable to perform a *global* water criticality assessment:

- anthropogenic climate change and probably a change in precipitation and evaporation patterns is mainly caused by the industrialized and newly industrialized countries - both probably not the regions which will suffer most from increased water shortages
- the impact of increased water withdrawals in one country often affects water availability in adjacent downstream countries (demands for catchment scale)
- international trade often substitutes domestic water withdrawals (demands for global scale)

In the following it will be shown that existing attempts for assessing water criticality do not address all relevant aspects and proposals will be made to approach an more integrated model of criticality.
The objectives of water criticality assessment are twofold:

- obtain a global overview on the current situation of water criticality to give general guidelines for effective international measures (development aid, dealing with international conflicts etc.)
- under the assumption of different development scenarios, possible future hot spots can be identified thereby giving the chance of precautionary measures

To get an overview on the state of the art of data availability and modelling approaches with respect to water availability, water quality, water demand and critical regions an extensive literature basis was studied. The references considered and their respective focus is listed in Appendix A.
In the next section on water demand (section 2) the water quality issue is discussed, the field of defining demand, need and substitutability is addressed and a critical review of statistical models for water withdrawal is given.
Then water availability modelling is discussed comprehensively including a systematic comparison of different global models (section 3). A suggestion which of the state of the art models would be most suited for a global criticality assessment is given.
Finally in section 4 existing approaches for global criticality measures are reviewed and the concepts of criticality ratio, water scarcity indices and criticality indices is discussed. The role of normative concepts is investigated.
From this detailed consideration of the state of the art several conclusions (section 5) are drawn with respect to next steps which are both, feasible and badly needed, to improve the quality of global water criticality assessments.

2 WATER DEMAND

Firstly some basic clarifications of terminology seem necessary, as the pragmatic work with the usually insufficient data basis results sometimes in confusing proxis and basic, systematic concepts. Figure 2.1. summarizes the “fate” of water withdrawal, stressing that water bodies are not only sources (withdrawal) but also sinks. The latter function is related to the availability problem as contaminated water is no more available for certain uses.

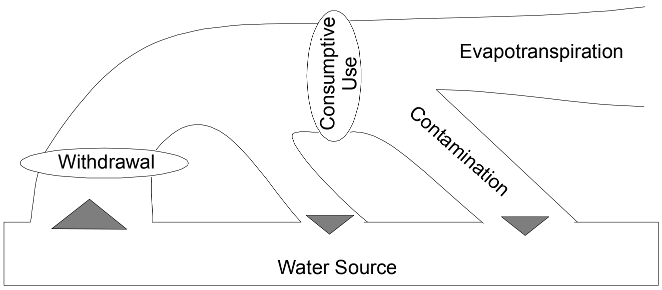


Figure 2.1: Some definitions: Water Source: Ground water, surface water. Non-consumptive use: e.g. cooling of power plants. Evaporation: mainly caused by irrigation. Contamination: waste water. Additional contamination of water bodies: imission by natural water flows/ solid.

2.1 The water quality issue

This makes clear that the aspect of water pollution has to be taken into account at least in a rough way to achieve a somewhat realistic picture of water use. In this paper a two dimensional minimum representation is suggested, as depicted in Figure 2.2, where – besides the usually used quantity axes - an additional aggregated quality axis is introduced. In Figure 2.2.A the general situation is depicted, while in Figure 2.2.B different water uses are distinguished.

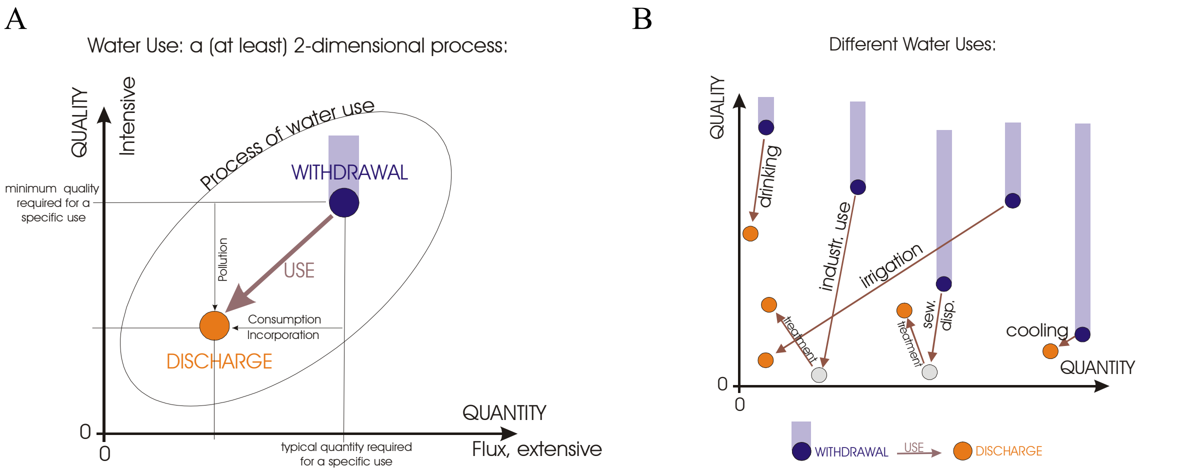
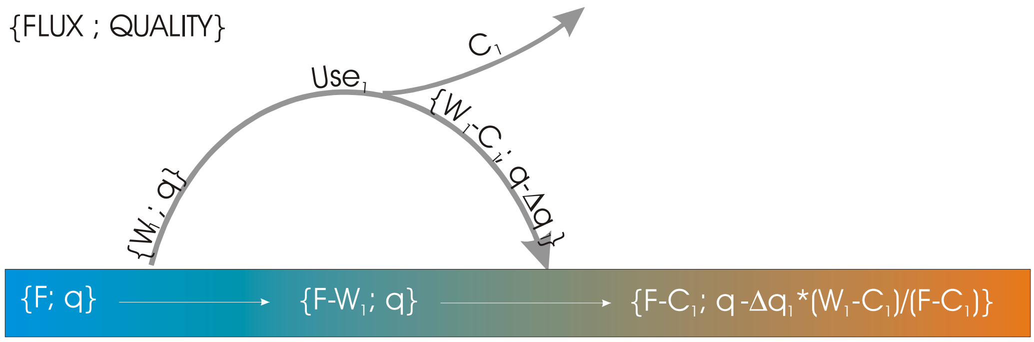


Figure 2.2: A: General structure of water use in the quality/quantity space. B: specific situation for different water uses.

The following diagram defines, how this two dimensional analysis has to be realized numerically, to obtain a time dependent picture of quantity and quality losses of, e.g., a river.

Change in quality and quantity of a stream under use



After a second use:

$\{F-C_1-C_2; q - \Delta q_1 * (W_1-C_1)/(F-C_1) - \Delta q_2 * (W_2-C_2)/(F-C_1-C_2)\}$

So far the impact of a specific water use can be principally described: even under bad data availability a poor estimation of water quality impacts is better that to omit it totally. In the following some citations from the “Comprehensive Assessment of the Freshwater Resources of the World”, United Nations Division for Sustainable Development 10/08/1999, illustrating the importance of considering quality:

“For millennia, people have used water as a convenient sink into which to dump wastes. The pollution comes from many sources, including untreated sewage, chemical discharges, petroleum leaks and spills, dumping in old mines and pits, and agricultural chemicals that are washed off or seep downward from farm fields. In one area after another, the amounts and types of waste discharged have outstripped nature's ability to break them down into less harmful elements. *Pollution spoils large quantities of water which then cannot be used, or at best can be used for restricted purposes only.”*

“In parts of the world, water quality has been so degraded that it is unfit even for industrial purposes.”

And some assessments of the situation in several world regions from the same source:

“A UN study found that in Latin America, virtually all domestic sewage and industrial waste is discharged untreated into the nearest streams. In most areas, domestic sewage volumes are far higher than those of industrial discharges. There were similar findings from West Africa, where there were signs of shallow aquifers being contaminated by the seepage of human wastes. In the Asia and Pacific region, in addition to domestic and industrial wastes, there are also high sediment loads in rivers resulting from high erosion upstream where much land is left exposed due to the removal of forest. The water pollution problems in many developing countries mirror those already experienced by developed countries in Europe and North America. A few decades ago some rivers in rich nations were so polluted that fires broke out on their oil-slicked surfaces. This was documented both in Canada and the United States. Due largely to public pressure, controls have been imposed on much of the gross pollution, and clean-ups are taking place, often at very high cost to the present generation. While much of the world's pollution is directly released from discharge pipes and sewers, or is carried off polluted industrial, municipal and agricultural areas by rainfall and melting snows, a significant pollution load is transferred long distances by the atmosphere.”

2.2 Demand, need and substitutability

The measure of water use is for pragmatic reasons often the observed/modelled value for withdrawal. Water need or demand are then often used synonymous – which is a confusing praxis. Of course the present withdrawal may be much lower than the demand, or even the need for water. Gleick (in Water in Crises, 1993) suggested the following definitions:

- NEED: minimum requirement to serve a certain purpose/requirement

- DEMAND: amount of water requested/required by a user – may have no relationship to minimum amount (NEED)

Here the whole discussion on basic needs, possibilities and right of development etc. applies. Statements like: "A region in a developing country is critical if the withdrawals necessary to reach the standard of living in Portugal (assuming present water use efficiencies) exceed the available water resource" have to be discussed.
A bit along this line the question arises which local water uses may be substituted by trading goods: the use of, e.g., irrigation water for the local production of agricultural goods can in principle be substituted by the import of the respective good. In this case the water withdrawal for the production of this good occurred elsewhere – possibly in a less water restricted region. So we can conclude that it is the demand for a specific agricultural good and not for a specific water withdrawal that is of importance.
Figure 2.3 summarizes which main types of water use exist and to what degree they are substitutable by trading of goods. Additionally, uses related to "basic needs" are marked and the role of water transport and desalination is considered. Finally the main factors specifying the use intensity are identified.

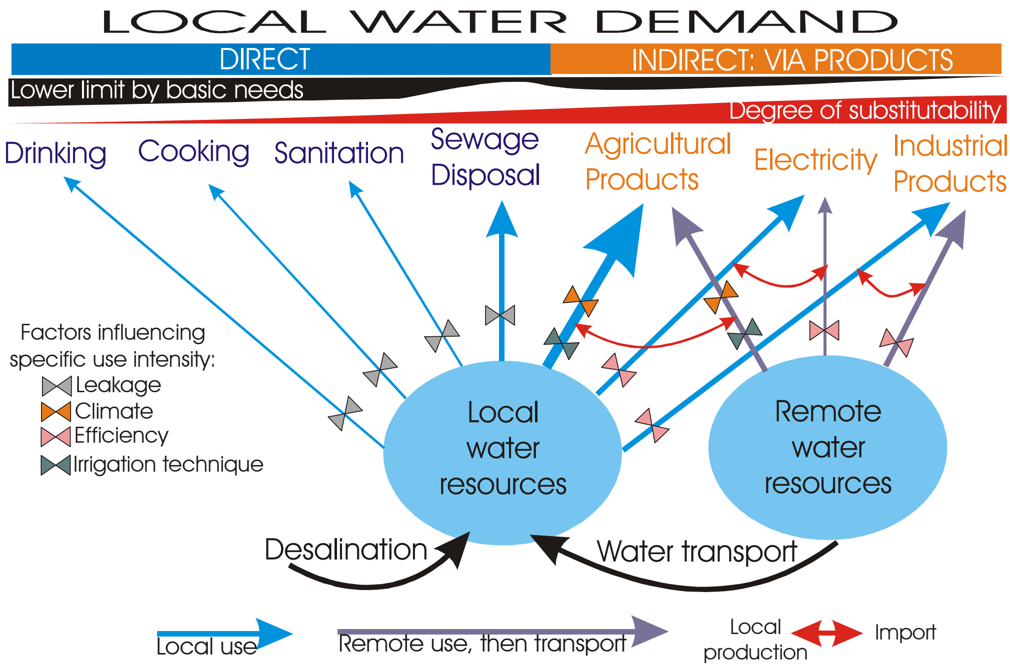


Figure 2.3: Substitutability of local water use and factors influencing use intensity.

Water in the global trading system is known as "virtual water". It is the water embedded in key water intensive commodities (Allan 1997). With respect to Agricultural water use the efficiency in irrigation can be improved (Postel 2001) but there are only narrow limits for increasing the efficiency of evapotranspiration of plants (e.g. by breeding, genetic engineering)
With respect to wheat trade Allan suggests that international it is a very effective and highly subsidised global trading system which operates to the advantage of water and food-deficit countries. And he further suggests that a major indicator of the scale of the water deficit of an economy is the level of its food imports.
With respect to Industrial water use: the potential of technological innovations is much greater than in the agricultural sector. Between 1980 and 1997 water consumption in industry has reduced by 22% (source BMU). For example, there has been 46% reduction of in the volume consumed per Mercedes-Benz passenger car since 1992. This has been achieved by installing closed-loop systems. Two DaimlerChrysler plants are located in Saltillo (Mexico)

in the middle of a desert area (Environmental Report 2000).

Table 2.1 give some examples for the "water content" of several products and shows that it is principally possible to consider virtual water via the global trade statistics. One can conclude that virtual water trade should be seen only as a complementary solution to increasing technical and productive efficiency of water use. In some regions, however, it already now has great importance.

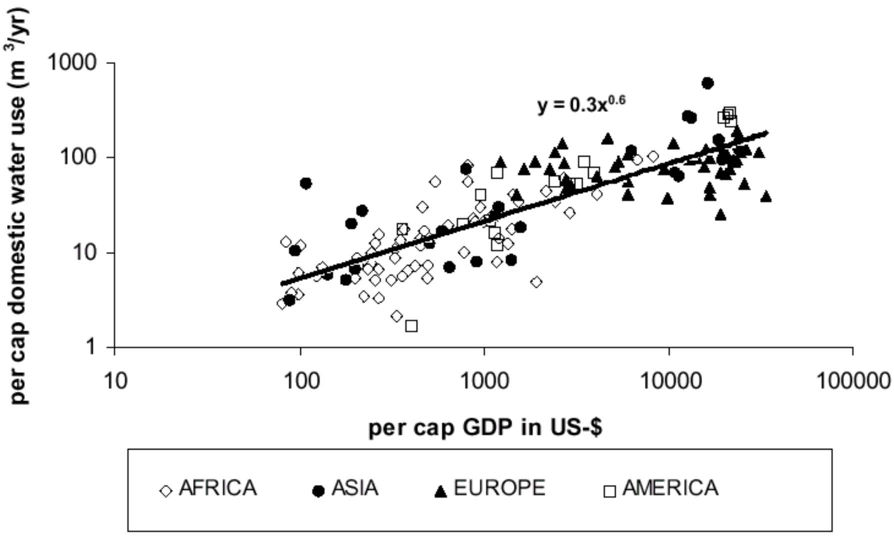
Product	Water needed for production	Source
2 kg wheat (1 kg bread)	1 m³	(Jaeger and Kasemir 2000)
Vegetarian diet (2500 kilocalories)	1 m³	(Jaeger and Kasemir 2000)
Mixed diet (2500 kilocalories) with 20% calorie uptake from meat	2 m³	(Jaeger and Kasemir 2000)
1 automobile	7 m³	DaimlerChrysler, environmental report 2000 (German passanger car plant)
1 automobile	50-100 m³	http://www.ggb.og.schule-bw.de/Aktivitaeten/Chemieprojekt/Haushalt.html#Industrie
1 kg paper	0,5 m³	http://www.ggb.og.schule-bw.de/Aktivitaeten/Chemieprojekt/Haushalt.html#Industrie
1 kg steel	O,18 m³	http://www.ggb.og.schule-bw.de/Aktivitaeten/Chemieprojekt/Haushalt.html#Industrie
1 kg sugar	0,18 m³	http://www.ggb.og.schule-bw.de/Aktivitaeten/Chemieprojekt/Haushalt.html#Industrie

Table 2.1.: Water contained in + used for the production of selected products.

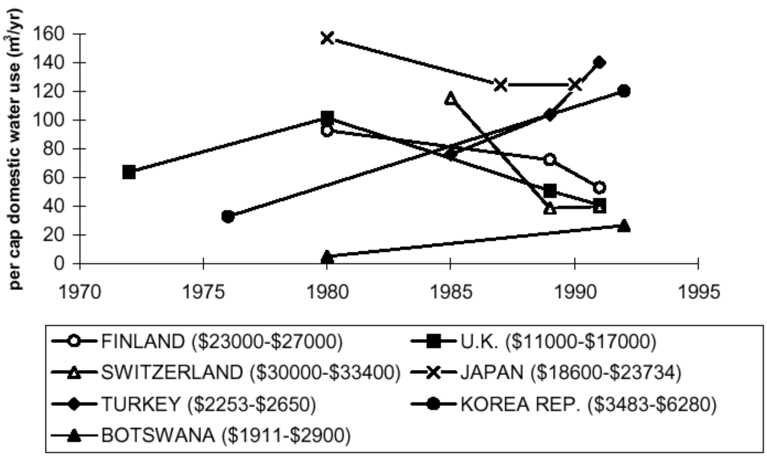
2.3 Proxis for predicting water use

To assess the current water use situation globally one has to refer to withdrawal data, which is problematic even under omitting the quality aspect (see Figure 2.1). Without considering quality aspects withdrawal overestimates water use.
Acamo, Döll et al. (1997) summarize: "Most water use data refer to withdrawal water use, which is divided into domestic, industrial and agricultural water use. Part of the withdrawn water is returned to its source or to another location (return flow). The difference between withdrawal use and return flow is referred to as consumptive use, i.e. the amount of water which evaporates due to its withdrawal. Thus, a user might reuse the water that has already been withdrawn by a first user who returns (part of) it to the stream. If return flow is high, like, for example, in the case of thermoelectric power plants (included in industrial water use), the amount of water used by two plants along a river in not much larger than that used by one. Then withdrawal use, which would be computed as the sum of the withdrawals for both plants, would overestimate the actual amount of water necessary to run the plants. On the other hand, consumptive use would underestimate it because for the first plant along the river, the amount equivalent to the withdrawal use of the first power plant must be available in the first place. Thus, actual water use lies between withdrawal and consumptive use. On a global scale, however, it is not possible to obtain this estimate. "
Fortunately, omitting pollution seems to correct at least in the right direction!

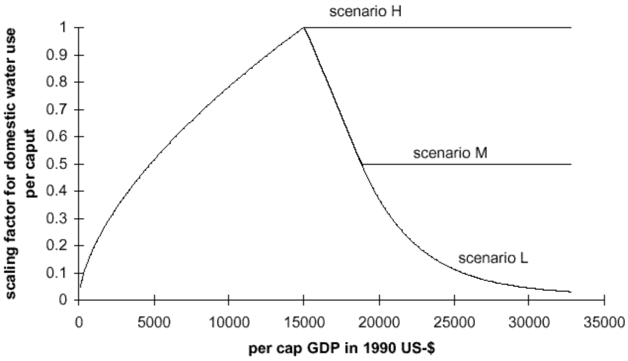
So, the current estimations on water use are only rough estimations which makes the identification of relations to other indicators even more complicated. In the following we illustrate the relatively poor quality of reconstructions of withdrawal data from GDP in the presently most advanced study, WaterGap.



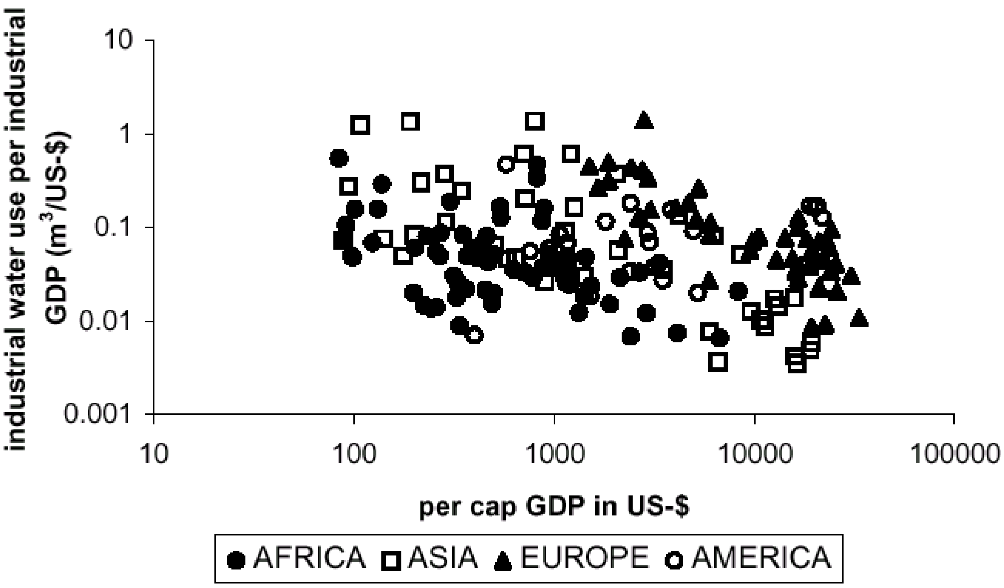
From WaterGAP 1.0, Fig. 3.1: Per cap domestic water use as a function of the per cap GDP. Shown are data from 112 countries (WRI, 1990, 1992, 1994, 1996). The value from the year closest to 1990 was selected for the calculation of the best fit line. Depending on the country, the depicted water use data are from the years 1980 to 1994. The country's per capita GDP is the GDP of the respective year in 1990-US$ (at constant prices) and was derived from data in UN (1995).



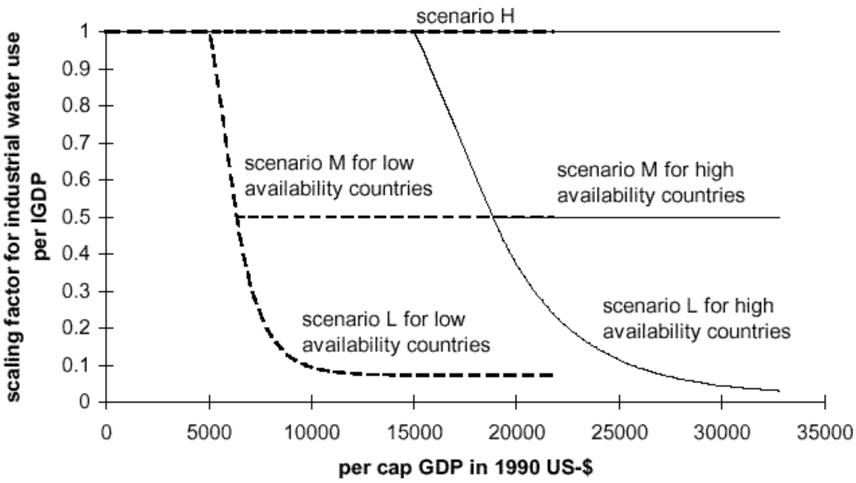
From WaterGAP 1.0, Fig. 3.2: Time series of per capita domestic water use in various countries. The GDP/cap-yr range during the respective time period is given in parentheses.



From WaterGAP 1.0, Fig. 3.3: Domestic water use scenarios.



From WaterGAP 1.0,Fig. 3.4: Industrial water use per industrial GDP as a function of per capita GDP in 112 countries: A really bad predictor for industrial water intensity - uncertainty amounts to **two orders** of magnitude:



From WaterGAP 1.0, Fig. 3.5: Industrial water use scenarios.

Her the shortcomings are obvious: to explain the use intensities only by the living standard does not work properly. Further explaining variables have to be taken into account to map important natural, economical and cultural influences.
All studies on global water reviewed have a very similar structure (water use is estimated by withdrawal) and are based mainly on population, industrial GDP (Gross Domestic Product) and GDP/capita to estimate water intensity. In some studies water withdrawal for agriculture is modelled more sophisticated considering climate, irrigated area and soil characteristics. Agriculture accounts for up about 70 percent of total human freshwater consumption on a global scale.

3 WATER AVAILABILITY

Five global water availability models were revied:

- WaterGap (Alcamo , Döll et al., 1997)
- the approach by Hagemann and Dümenil (Hagemann and Dümenil, 1997)
- the approach by Renssen and Knoop (Renssen and Knoop, 2000)
- Water Balance by Vörösmarty (Vörösmarty et al., 2000)
- the approach by Arnell (Arnell,1999)

with respect to consistency, crucial limitations and missing components. The following Table 3.1. shows exemplarily, how the different models were evaluated along the criteria given in the first column.

MODEL/ AUTHOR	**WBM/ WTM (water balance/ transport model) / Vörösmarty**
1. GENERAL	
1.1 Purpose	global scale water balance and transport, also as part for terrestrial ecosystem model TEM (McGuire et al., 1997)
1.2 Spatial discretisation	WBM: 0.5 x 0.5 ° grid WTM: streamflow network and sub-basin delineation
1.3 Temporal discretisation	daily, monthly or mean-monthly
2. INPUT DATA	
2.1 Input climate data	precipitation and air temperature
2.2 Input surface data	land cover, elevation, rooting depth, soil texture (AWC)
3. HYDROLOGY	
3.1 Snow	empirical function of temperature and elevation with linear detention pool for snowmelt
3.2 Interception	--
3.3 Evapotranspiration	Thornthwait and Mather (1957) or others
3.4 Soil water balance	$dW/dt = -g(W) (Ep-P)$ with $g(W)$ soil drying function, excess water is stored in a detention pool and released proportional to current storage
3.5 Groundwater	together with soil water detention pool
3.6 Land routing	together with river routing (see 3.7)
3.7 River routing	linear reservoir with floodplain sub-storage (inundation)
4. RELATED MODULES	
(e.g. sediments, erosion, phosphorous, nitrogen, crop yield)	--

5. VERIFICATION	
5.1 global	comparison with long-term annual GRDC station observations
5.2 continental	- Amazon basin: calibration monthly for 3 stations (1982-84), no separate validation period - South America: calibration mean monthly for 6 sampling stations, no separate validation period
6. REFERENCES	(for complete references see Appendix A)
	Fekete et al. (2000), Vörösmarty et al. (2000), Vörösmarty et al. (1998), Vörösmarty et al. (1996), Vörösmarty et al. (1989)
7. STATEMENT	
Summary statement of reviewer (applicability, advantages +, disadvantages -)	+ seems to be a simple but robust approach + contains scaling version of dW/dt for applications of monthly forcings using the probability of a wet day within a month and an exponential distribution for precipitation amounts + simultaneous solution of resulting differential equations for WBM and WTM - very little validation exercises - no application on daily data reported - global application only using long-term mean monthly forcings

Table 3.1: Evaluation of the Vörösmarty model – the other 4 models were treared analogously.

In the following Table 3.2 desirable properties of a water availability model used for a global water criticality assessment are summarized.

No.	What	How	Why
SCALE			
1	spatial scale	grid 0.5°	- allows almost any aggregation to catchments and countries - link to global climate models
2	subgrid scale variability	statistically	- accounts for poor (averaged) soil information by introducing some more variability
3	time scale	daily	- compromise between data availability and processes
INPUT DATA			
4	climate	precipitation, temperature, some kind of radiation info (e.g. sunshine hours, cloudiness)	- radiation substitute required for reasonable ETP with restricted global data availability
5	land use	land use (at least as many classes as LPJ including agriculture)	- reasonable ETR - for land use change assessments - link to agricultural water demand assessment
6	soil	field capacity, porosity, sat. hyd. conductivity, root depths	- allows sufficient parameterisation of soil water model without (much) calibration

OUTPUT DATA			
7	runoff	two runoff components (base flow and direct flow) on monthly resolution (-> requires soil moisture dynamics, groundwater accounting and routing within grids)	- allows better overall simulation performance - necessary for differentiation between total and some kind of stable water resources (base flow only) - get seasonality
8	discharge	discharge for each (river) grid cell (-> requires routing between grids)	- inflow/ outflow for administrative units (e.g. countries)
9	evaporation	monthly grid based	- land use change effects and agricultural management
*10 *1*	*water quality indicator*	*mean monthly for each (river) grid cell*	- *required for advanced criticality assessments*

*1: would require additional input (e.g. population density, sewage treatment potential, fertilizer application)

Table 3.2: Desirable properties of a water availability model for global criticality assessments.

From the five reviewed models the water balance models of Vörösmarty and Arnell are the most consistent. However both have crucial limitations and missing components. For example water quality (transport and dilution of pollutants), which is crucial for different types of water uses is not considered in the models. Further on the representation of the dynamics of vegetation (natural and agricultural) is rudimentary yielding poor prognosis of evapotranspiration under Global Change scenarios.

4 CURRENT APPROACHES TO IDENTIFY CRITICAL REGIONS

In most studies the *potentially available renewable water resource* (PARWR) for a given region (e.g. country) and time-span (mostly: one year):

rainfall – evapotranspiration + surface inflow

is compared with the observed withdrawal (W). If

(a) W is a high percentage of PARWR (CR=W/PARWR near 1) and
(b) PARWR per capita is low (“water competition” is high)

the region is identified as critical (high water scarcity index, WSI). The usually cited source for this definition is Kulshreshtha (1993). Here the WSI-values in the following table describe different scarcity situations: 1: freshwater surplus, 2: low vulnerability, 3: freshwater stress, 4: freshwater scarcity.

	Ratio W/PARWR			
PARWR per capita (m^3 per annum)	<0.4	0.4–0.6	0.6–0.8	>0.8
<2,000	2	3	4	4
2,000–10,000	1	2	3	4
>10,000	1	1	2	4

This measure is obviously rather heuristic, but it produces – using available data bases or model results (the uncertainty of both has to be discussed) - on a global scale (with nation- or catchment-wide resolution) more or less plausible maps (Alcamo, Döll et al.,1997 WBGU1999, United Nations Division for Sustainable Development 10/08/1999). The problem is that this measure relies on a lot of implicit assumptions which make both, the interpretation of the results and the application on finer scales, rather questionable.

4.1 Relation between CR, WSI and criticality

What is the difference of using 50% instead of 70% of PARWR with respect to criticality? This is mapped - due to the above table independent of per capita availability – on an increase in WSI. On the other hand the difference in effort to make available 70% in one country or 50% in another is obviously determined significantly by factors not represented by CR (like rainfall-pattern, topography, withdrawal-pattern etc.). Furthermore there is in both cases (in principle) a large "reserve" of potentially available water for future additional use (e.g. due to population increase or increased irrigation in agriculture). The question of interest is: how much effort is necessary and how severe are the environmental and social consequences to mobilize the next 10% of PARWR.
When interpreting the CR-results the consideration of these factors may simply revert the critically ranking as predicted by CR – assumptions of statistical correlations between CR and the decisive factors are not proven.
The only value of CR with a definite interpretation is "near 1" (see last column of the above table): there is no leeway for future additional use on the basis of local renewable resources, or, respectively, high vulnerability towards potential changes in availability (via climate change, reduction of influx from other countries, pollution etc.). Beside this the ranking of regions with CR less than one is questionable.
With respect to the second independent variable of WSI, no detailed qualification of PARWR/cap. is considered. Depending on the climatic situation (for agricultural and household use) and the structure of industry different amounts of water use should be sufficient.
Unfortunately the problem in interpreting CR holds for the attempt of Falkenmark and Lindh (in Water in Crises, 1993) of classifying countries in a more qualitative way due to the following scheme:

Present withdrawal level	Present mobilization level (CR)	
	High	Low
High	α	β
Low	γ	δ

Now for each class general options to cope, e.g., with population growth can be identified:
α: reduction of water use (rationing, increased use efficiency)
β: modernizing resource development
γ: tremendous task
δ: large degree of flexibility

An extension done by the WBGU (1999) considers the ability of a country to substitute scarce natural resources (in this case freshwater) by capital. This ability is approximated by the wealth of a country, measured as GDP/cap. WSI and this measure for "adaptive capacity" were combined as showed in Figure 4.1, where two viewpoints concerning the general possibility of successful substitution are considered to address the uncertainty of economic sciences in this field. In Figure 4.2 the global result for the low substitutability is shown.

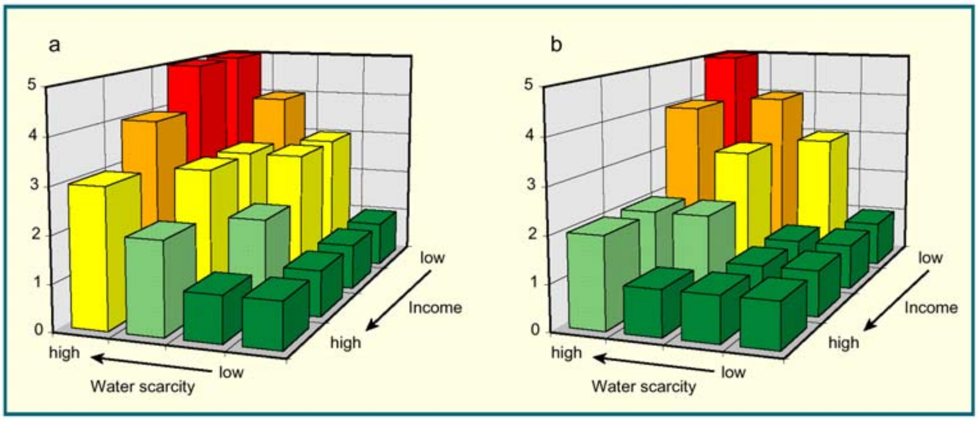


Figure 4.1 a: low substitutability of water scarcity (as stated by "ecological economics") b: high substitutability of water scarcity (as stated by "standard economics") GREEN: situation NOT CRITICAL RED: situation HIGHLY CRITICAL

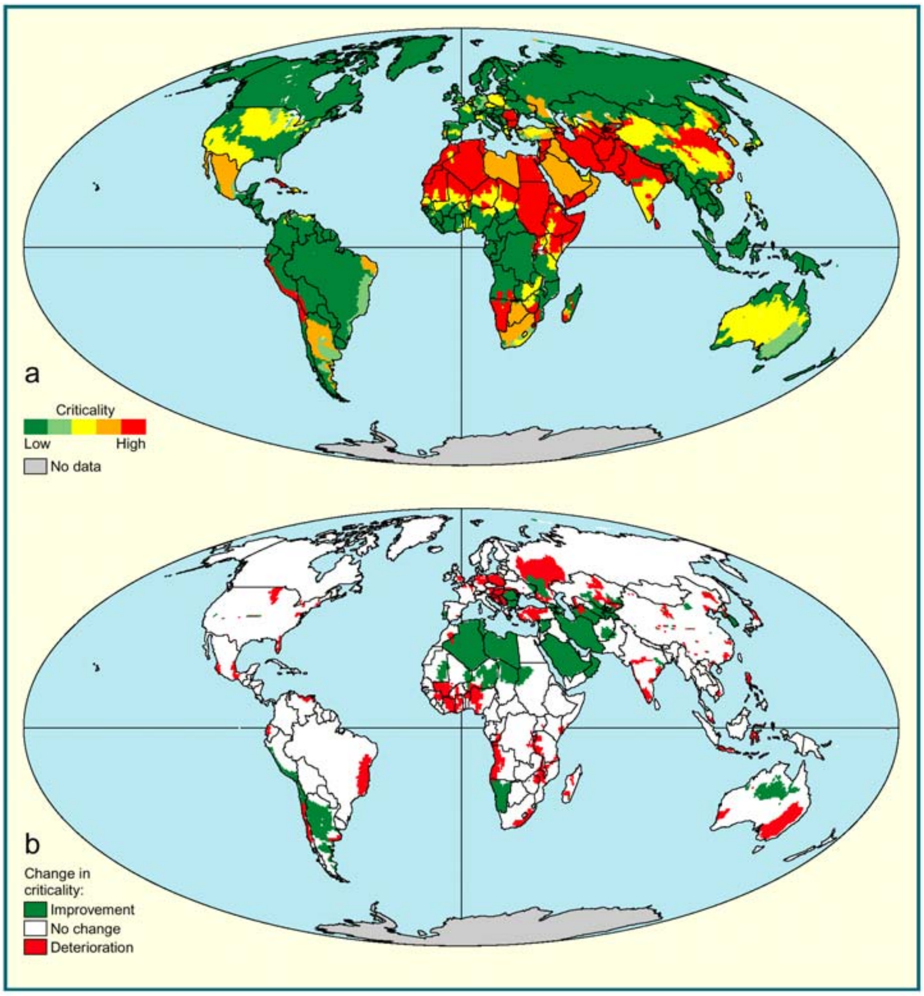


Figure D 3.1-2
Scenario II and difference in 2025. a) Criticality index in 1995, assuming low substitutability (Scenario II). b) Change in criticality index to 2025, assuming the middle scenario for water withdrawals and the IS92a IPCC forecast for economic growth and population trends. Climate trends are based on output from the ECHAM 4 coupled atmosphere-ocean GCM (MPI for Meteorology and Climate Computing Center, Hamburg), driven by the IS92a CO_2 emissions scenario. Note that the large areas where improvements are indicated have low population densities in many cases (see Fig. D 3.1-4 for an analysis in which population is a weighted factor) and that "no change" may signify the perpetuation of a serious water crisis.
Source: BMBF "Syndrome Dynamics" project, PIK Core Project QUESTIONS and WBGU, using also Alcamo et al., 1997

Figure 4.2: Resulting actual criticality and future change under plausible demographic and economic scenarios

4.2 Withdrawal: Overuse or Underuse?

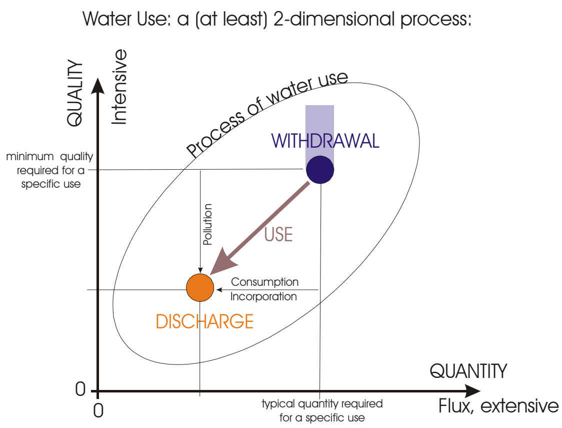
The measure of criticality uses the observed/modelled value for withdrawal (W). Water need or demand are then often used synonymous – which is somewhat confusing. Of course the present withdrawal may be much lower than the demand, or even the need for water. Gleick (in Water in Crises, 1993) suggested the following definitions:

- NEED: minimum requirement to serve a certain purpose/requirement
- DEMAND: amount of water requested/required by a user – may have no relationship to minimum amount (NEED)

Here the whole discussion on basic needs, possibilities and right of development etc. applies.
Statements like: “A region in a developing country is critical if the withdrawals necessary to reach the standard of living in Portugal (assuming present water use efficiencies) exceed the PARWR” have to be discussed.
Another critical point are sub-scale mismatches (in time t and space r) between W(r,t) and PARWR(r,t). Only under optimal natural conditions or optimal technical equipment (t-mismatch: reservoirs; r-mismatch: water transport) the calculated CR is valid for the whole region – in general this will be not the case

5 CONCLUSIONS

With respect to water demand several studies were reviewed. These have a very similar structure (water use is estimated by withdrawal) and are based mainly on population, industrial GDP (Gross Domestic Product) and GDP/capita to estimate water intensity. In some studies water withdrawal for agriculture is modelled more sophisticated considering climate, irrigated area and soil characteristics. Efficiency in irrigation can be greatly improved but there are rather narrow limits for increasing efficiency of evapotranspiration of plants (e.g. by breeding or genetic engineering). In future research water demand has to be specified according to quality of water needed for a specific purpose. A feasible way should be the introduction of an aggregated quality dimension.



With respect to water availability five global water availability models (WaterGap, the approach by Hagemann and Dümenil, the approach by Renssen and Knoop, Water Balance by Vörösmarty, and the approach by Arnell) were reviewed. The conclusion is that the water balance models of Vörösmarty and Arnell are the most consistent. However both have crucial limitations and missing components. For example water quality (transport and dilution of pollutants), which is crucial for different types of water uses is not considered in the models. Further on the representation of the dynamics of vegetation (natural and agricultural) is rudimentary yielding poor prognosis of evapotranspiration under Global Change scenarios

which could be improved by coupling with dynamic global vegetation models (like the Lund-Potsdam-Jena-DGVM).
With respect to water criticality different measures in global water assessments were studied. They are all based on the relation between water withdrawal and available water (e.g. severe scarcity above 40%) and on the other hand they are based on per capita minimum requirements. Therefore normative aspects play a crucial role in assessing water criticality. Open questions include: What is the fair amount of water? There is also no general agreement on what “water criticality” actually is. Cultural differences, coping mechanisms and technological change play a key role in this respect. One definition of criticality could be that a region is critical if the withdrawals necessary to reach the standard of living in, e.g. Portugal (assuming present water use efficiencies) exceed the potentially available renewable water resource. The possible level of substitution plays a key role for water criticality as well. For example in water scarce regions agriculture can be substituted by importing food, assuming that the development of other economic sectors allows this. Such projections can be made with the help of economic modelling. Two possible steps include (a) using a computable general equilibrium (CGE) model (GTAP databank and model) with fixed or prescribed water efficiencies or (b) using a growth model including endogenous change with respect to water efficiency. The first can be easily adapted and modules of the second type are currently under development (e.g. the MIND model at PIK for CO_2 efficiencies).
An important requirement is that a water criticality measure should be able to map the influence of the four existing main management options and their combinations: structural measures (increasing supply by building dams, diverting rivers, pipelines, etc.), substitution (virtual water i.e. water included in water intensive commodities), improving efficiency (for example technological solution in industry, end-of-pipe water treatment, improved irrigation) and micro-solutions (“capture rain where it rains”, watershed management). In the concluding Figures 51 and 5.2 the “state of the art” and most necessary and feasible improvements are summarized.

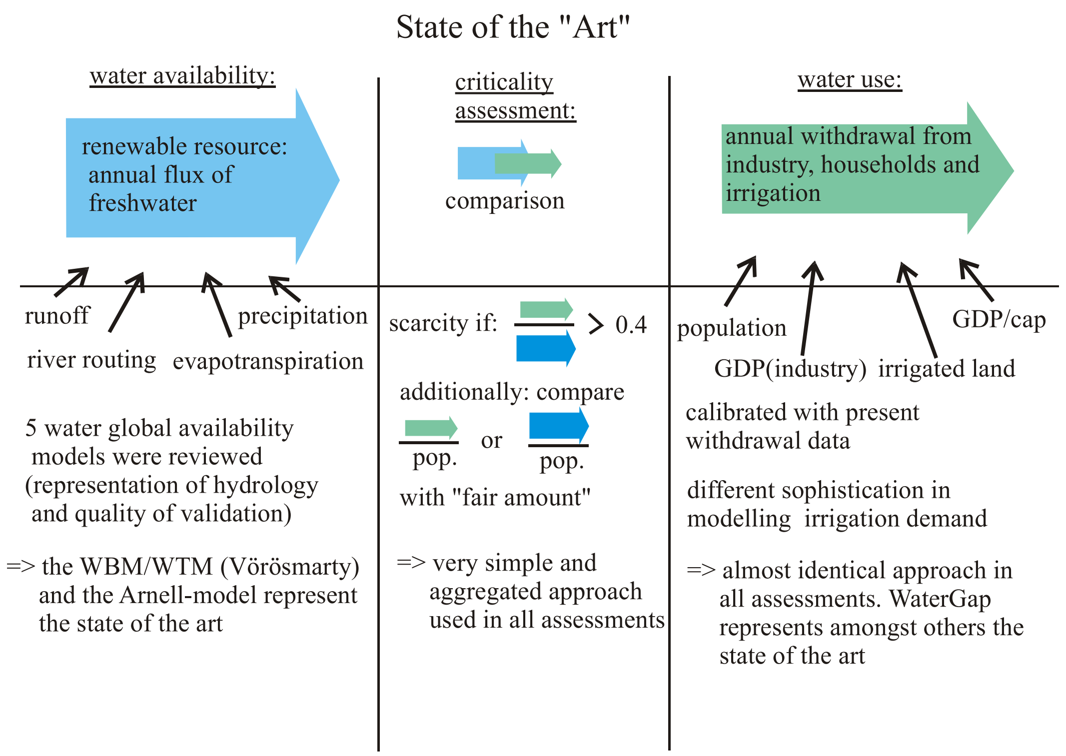


Figure 5.1: “state of the art” of current global freshwater criticality models

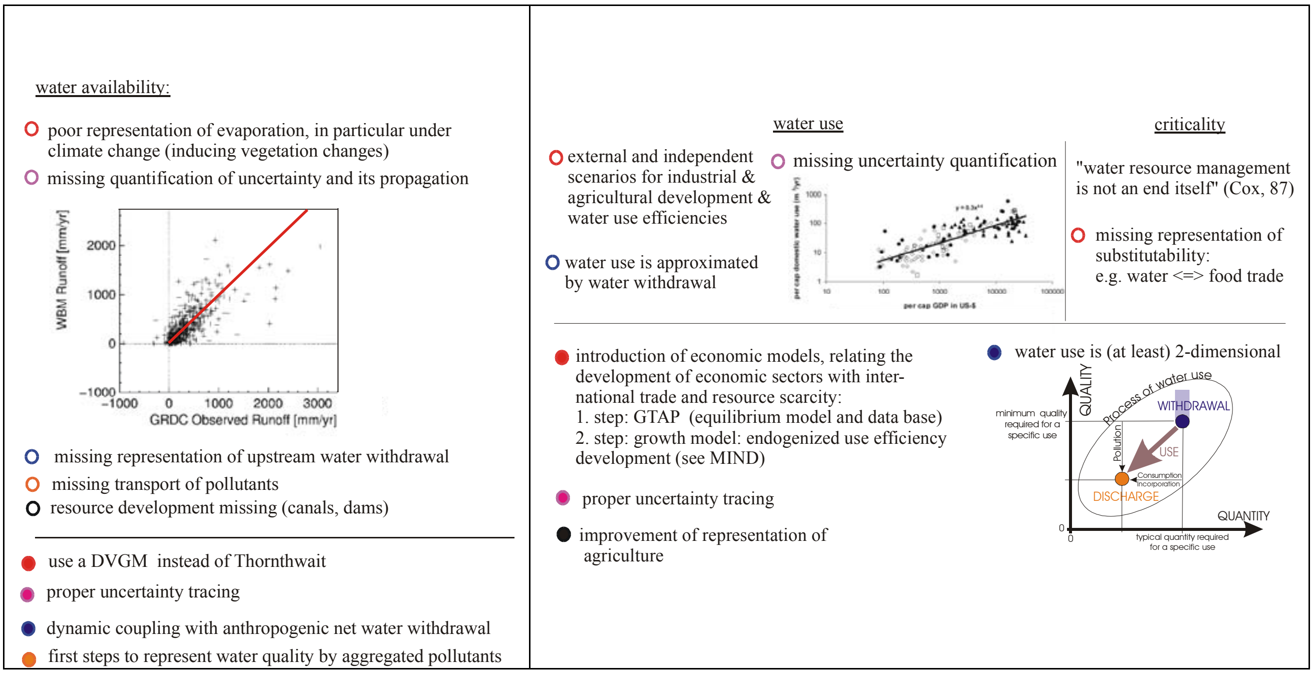


Figure 5.2: Severe shortcomings of current models and most necessary and feasible improvements.

6 REFERENCES

Alcamo, Josef, Petra Döll, Frank Kaspar and Stefan Siebert (1997) Global change and global scenarios of water use and availability: An Application of WaterGAP1.0. Center for Environmental Systems Research (CESR), University of Kassel, Germany

Allan, J. A. (1997). 'Virtual water': a long term solution for water short Middle Eastern economies? British Association Festival of Science, Water and Development Session, Leeds, UK

Comprehensive Assessment of the Freshwater Resources of the World. Report of the Secretary-General. United Nations Division for Sustainable Development 10/08/1999 (http://www.un.org/esa/sustdev/freshwat.htm#Intro)

Jaeger, C. C. and B. Kasemir (2000). Global Water Resources and the Role of Europe, VISIONS working paper, January 2000**:** 18

Kulshreshtha, S. N. (1993): World Water Resources and Regional Vulnerability: Impact of Future Changes. Laxenburg: IIASA

Falkenmark/Lindh in Water in Crises, Gleick, P.H. (ed.) 1993

Gleick, P.H. ed (1993) Water in Crisis. A Guide to the World's Fresh Water Resources. Oxford University Press, New York, Oxford

Postel, S. (2001). “Growing more Food with Less Water.” Scientific American **284**(2): 34-37

WBGU:German Advisory Council on Global Change (1999). World in Transition: Ways

Towards Sustainable Management of Freshwater Resources. Springer Verlag, Berlin

World Resources Institute (WRI) (1990, 1992, 1994, 1996)

7 APPENDIX A

Sources considered in the present study to identify the state of the art: in general not explicitly cited in the paper.

Categories addressed in the respective sources:

WA	-	water availability
WQ	-	water quality
WD	-	water demand
M/CR	-	management/ critical regions
CM	-	coupled modelling (hydrologic components in global models)
VP	-	vision papers

Author	Year	Title	Where	Cat
Alcamo, J. et al	1998	Global Change Scenarios of the 21st Century, Results from the Image 2.1 Model	Elsevier Science, Pergamon.	
Alcamo, J.; Döll, P.; Kaspar, F.; Siebert, S. c	1997	Global change and global scenarios of water use and availability: An application of WaterGap 1.0.	WZ-Report A9701, Centre for Environmental Systems Research, University of Kassel. http://www.usf.uni-kassel.de/service/bibliothek	WA WD
Arnell, N. W.	1999	Climate change and global water resources.	Global Enviromental Change, Volume 9 S31-S49.	WA
Arnell, N.W.	1999	A simple water balance model for the simulation of streamflow over a large geographic domain.	J. Hydrol. 217(3-4), 314-335	WA
Baumgartner, A. & Reichel, E.	1975	The World Water Balance.	Amsterdam, Elsevier.	WA
Challen, R.	2000	Institutions, Transaction Costs and Environmental Policy. Institutional Reform for Water Resources.	Edward Elgar Publishing Limited	M/CR
Coe, M.T.	1998	A linked global model of terrestrial hydrologic processes: Simulation of modern rivers, lakes, and wetlands.	J. Geophys. Res. 103, No.D8, 8885-8899	WA
Creighton, J. L.	1999	Tools and Techniques for Effective Public Participation in Water Resources Decision. Participatory processes in water management.	Satellite Conference to the World Conference on Science., Budapest, Hungary, UNESCO, International Hydrological Programme	M/CR
Engelman, R. & LeRoy, P.	1993	Sustaining Water - Population and the Future of Renewable Water Supplies.	Population and Enviroment Program. Population Action International.	WD WA

Entekhabi, D.; Asrar, G.R.; Betts, A.K.; Beven, K.J.; Bras, R.L.; Duffy, C.J.; Dunne, T.; Koster, R.D.; Lettenmaier, D.P.; McLaughlin, D.B.; Shuttleworth, W.J.; Genuchten van M.T.; Wie, M.-Y.; Wood, E.F.	1999	An agenda for land surface hydrology research and a call for the second international hydrological decade.	Bulletin of the American Meteorological Society, 80(10), 2043-2058.	VP WA CM
F. R. Rijsberman (ed.)	1995	World Water Scenarios: Analysis.	World Water Council	
Falkenmark, M. & Lindh, G.	1976	Water for a Starving World.	Westview Press, Boulder, CO.	WD
Fekete, B.M., Vörösmarty, C.J., Grabs, W.	2000	Global, composite runoff fields based on observed river discharge and simulated water balances.	UNH/GRDC Composite Runoff Fields V 1.0, CD	WA
German Advisory Council on Global Change	1997	World in Transition: Ways towards Sustainable Development of Freshwater Resources.	http://www.wbgu.de/wbgu_veroeffentlichungen.html	WD WA
Gleick, P. H.	1998	The world's water 1998 – 1999: The biennial report on freshwater resources.	Island Press, Washington D.C.	WD WA M/CR
Gleick, P. H.	2000	The world's water 2000 – 2001: The biennial report on freshwater resources.	Island Press, Washington D.C.	WD WA M/CR
Gleick, P. H. ed.	1993	Water in Crisis. A Guide to the World's Fresh Water Resources	Oxford University Press, New York, Oxford.	WA WD
Gleick, P.H. (Lead Author)	2000	Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States.	http://www.gcrio.org/NationalAssessment/	WA
Hagemann, S.; Dümenil, L.	1998	A parameterization of the lateral waterflow for the global scale.	Climate Dynamics, 14, 17-31.	CM WA
Hoekstra, Arjen Y	1998	Perspectives on Water. An Integrated Model-based Exploration of the Future.	International Books	WA DM
Jaeger, C. C. and B. Kasemir	2000	Global Water Resources and the Role of Europe	VISIONS working paper, January 2000**:** 18. http://www.icis.unimaas.nl/visions/	M/CR
Kacmarek, Z., editor ,	1996	Water resources management in the face of climatic/hydrologic uncertainties, Water Science and Technology Library	IIASA.	WD
Klepper, O.	1996	Documentation for the calculation of world-wide water satisfaction on catchment basin level.	Unpublished report, RIVM, The Netherlands.	WD WA
Kulshreshtha, S. N.	1993	World Water Resources and Regional Vulnerability: Impact of Future Changes.	IIASA, June 1993.	WA WD
Moral L.D & Sauri, D.	1999	Changing Course: Water Policy in Spain.	Environment **41**(6): 12-36.	M/CR
Olivera, F.; Famiglietti, J.; Asante, K.	2000	Global-scale flow routing using a source-to-sink algorithm.	Water Resources Research, 36(8), 2197-2207.	CM WA

Postel, S.	1984	Water: Rethinking Management in an Age of Scarcity.	Worldwatch Paper 62 December 1984.	M/CR
Priscoli, J.D.	1999	What is public participation in water resources management and why is it important?	Satellite Conference to the World Conference on Science., Budapest, Hungary, UNESCO, International Hydrological Programme	M/CR
Renssen, H. and Knoop, J	2000	A global river routing network for use in hydrological modeling	Journal of Hydrology 230, 230-243	
Rodriguez-Iturbe, I.	2000	Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics.	Water Resources Research, 36(1), 3-9.	VP CM WA
Schultz, G.A.; Hornbogen, M.; Viterbo, P.; Noilhan, J. (eds.)	1995	Coupling large-scale hydrological and atmospheric models.	IAHS Special Publication No. 3, IAHS Press, Wallingford	CM WA
Shiklomanov, I.	2000	Appraisal and Assessment of World Water Resources	Water International, 11-32.	WA
Shiklomanov, I.	1999	Asessment of water resources and water availibility in the world. Report to the World water Commission.	World water Commison	WA
Shiklomanov, I. A.	1997	Assesment of Water Resources and Water Availability of the World, Background Report for the Comprehensive Assessment of the Frershwater Resouces of the World.	WMO, Geneva, manuscript (published later in a CD-form in UNESCO)	WD WA
Slutsky, A.H. and Yen, B.C.	1997	A macro-scale natural hydrologic cycle water availability model.	J. Hydrol. 201, 329-347.	WA
Stockholm Environment Institute (ed.)	1997	Comprehensive assessment of the freshwater resources of the world. 8 reports.	SEI, Stockholm	WA, M/CR ,WD, WQ
Uitto, J. I.	1997	Environmental governance and the impending water crisis	Global Environmental Change **7**(2) : 167-173	M/CR
United Nations	2000	Water Management: Public Participation and Compliance with Agreements	United Nations**:** 57.	
Vörösmarty, C.J. ; Moore, B. ; Grace, A.L., Gildea, M.P., Melillo, J.M. ; Peterson, B.J., Rastetter, E.B. ; Steudler, P.A.	1989	Continental scale models of water balance and fluvial transport: An application to South America.	Global Biogeochem. Cycles, 3, 241-265.	WA WQ
Vörösmarty, C.J., Federer, C.A. and Schloss, A.J.	1998	Potential evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling.	J. Hydrol., 207(3-4), 147-169	WA
Vörösmarty, C.J., Willmott, C.J., Choudhury, B.J., Schloss, A.L., Stearns, T.K., Robeson, S.M., Dorman, T.J.	1996	Analyzing the discharge regime of a large tropical river through remote sensing, ground-based climatic data, and modeling.	Water Resour. Res. 32(10), 3137-3150.	WA
Vörösmarty, C.J.; Green, P.; Salisbury, J.; Lammers, R.B.	2000	Global water resources: vulnerability from climate change and population growth.	Science, 289, #5477, July 14, 284-288.	WA WD

White G.F.	2000	Water Science and Technology. Some Lessons form the 20th Century	Environment **42**(1) : 30-38	M/CR
World Bank	1999	World Development Report 1998/99.	Knowledge for Development, Oxford Univ. Press.	WM
World Water Commission	2000	A Water Secure World. Vision for Water, Life and the Environment	World Water Council**:** 83.	M/CR
Yates, D. N.	1997	Approaches to continental scale runoff for integrated assessment models.	J. Hydrol. 201, 289-310.	WA WD