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Blue limits of the Blue Planet: an exploratory analysis of safe operating spaces for human water use under deep uncertainty

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Abstract. *In the Nature article 'A safe operating space for humanity', Rockström et al. (2009) introduce the concept of a safe operating space for humanity. A safe operating space is the space for human activities that will not push the planet out of the 'Holocene state' that has seen human civilizations arise, develop, and thrive. Rockström et al. have identified nine earth-system processes and associated thresholds which, if crossed, are expected to generate unacceptable environmental change. These include among others climate change, rate of biodiversity loss, interference with the nitrogen and phosphorus cycles, and global freshwater use. Rockström et al. provide only a best guess for the limits to global freshwater use. Molden (2009) concurs with Rockström et al. that there are physical limits to human interventions in natural processes. However, these limits are critically depended on local conditions, the role of management, and financial and institutional capacity in magnifying or ameliorating problems, and estimates of these limits are plagued by uncertainty. In case of the limits to the world water system, these uncertainties arise out of conflicting models, regional variations, limitation of expansion of water use through financial and institutional capacity, and uncertainty about the realization and efficiency of trans-boundary water transfers. This paper aims at investigating more thoroughly the limits to global freshwater use. To this end, the behavior of a dynamic model of the world water balance is explored across a wide variety of uncertainties. We find that the dynamics at a global level are not substantially affected by this. This is explained in light of the order of magnitude difference between annual human water use and annual runoff.*

Keywords. Exploratory modeling and analysis, global change, safe operating space, global limits, ANEMI, world water models, uncertainty

1 Introduction

In the *Nature* article 'A safe operating space for humanity', Rockström et al. (2009) introduce the concept of a safe operating space for humanity. A safe operating space is the space for human activities that will not push the planet out of the 'Holocene state' that has seen human civilizations arise, develop, and thrive. The concept is inherently anthropocentric and excludes non-human events and processes that could push the planet out of the Holocene state. Rockström et al. have identified nine earth-system processes and associated thresholds which, if crossed, are expected to generate unacceptable environmental change. These include climate change, rate of biodiversity loss, interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading. For all nine earth-system processes identified associated preliminary boundaries are given by Rockström et al. (2009). However, for only three of them, notably, climate change, rate of biodiversity loss, and the nitrogen cycle, are these boundaries substantiated theoretically and methodologically. The thresholds for the other six, including the global fresh water cycle, are tentative 'best guesses' (Rockström et al. 2009). For water, Rockström et al maintain that the boundary must be set to safely sustain enough green water for moisture feedback while allowing for terrestrial and aquatic ecosystem functioning and as a first attempt propose runoff depletion in the form of consumptive blue water use as a proxy. Based on global fresh water cycle assessment studies, Rockström et al set the threshold for global fresh water use at a range of 4000 to 6000 cubic kilometers per year.

Although we do subscribe to Rockström et al.'s ambition and concepts, there are nevertheless several problems associated with the approach they advance. A first problem is the ambiguous treatment of reductionism versus holism. While the authors clearly recognize thresholds and threshold behavior as a systemic and emergent property, Rockström at al. embark on a reductionist approach by reducing the earth system to nine biophysical processes and define planetary boundaries internal to these subsystems. Such an approach is bound to overlook the impacts of the dynamic interactions between the subsystems. To this, Molden (2009) add that the concept of a global limit overlooks the importance of local conditions, regional variations, the role of management, and financial and institutional capacity in magnifying or ameliorating problems. Moreover, the estimate of the global limit for blue water use is based on a limited number of studies extrapolated beyond their original intentions (Molden 2009). Furthermore, structural uncertainties exist in the relation between climate change and renewable fresh water resources (RFWR) (Oki and Kanae 2006).

From the foregoing, we conclude that the hypothesis of Rockström et al. that humanity may soon be approaching the boundaries for global freshwater use is disputed. Much of this dispute relates to uncertainties in the interaction between socio-economic and physical factors in the approach used for establishing the safe operation space with respect to water use and the consequences of climate change. That is, the limits on fresh water use cannot be established without considering related subsystems and the wide variety of uncertainties. The reductionist and complex dynamics issues are tackled by utilizing an integrated dynamic models of the planetary fresh water cycle that takes into consideration the non-linear and dynamic feedback relationships between physical characteristics of water balance and population growth; development of agriculture and industry; technological development and use of other resources. The issue of uncertainty is addressed by applying Exploratory Modeling and Analysis (EMA), a research methodology that uses computational experiments to analyse complex and uncertain systems (Agusdinata 2008, Bankes 1993). The remainder of this paper is structured as follow. Section 2 outlines the method in more detail. Section 3 contains the application and results. Section 4 contains an extended discussion of the results.

2 Method

There are various modeling approaches that can be used to model the planetary fresh water cycle. One modeling approach that fits with the suggested holistic approach is system dynamics (Sterman 2000, Forrester 1968). At present, several integrated dynamic water cycle models exist at both global and regional scales. These models have been used to define global or regional limits to the use of blue water. On a global scale, AQUA (Hoekstra 1998) and WorldWater (Simonovic 2002) are the most relevant and best known models. ANEMI is a more recent model in this same tradition (Davies and Simonovic 2010, Davies and Simonovic 2011).

The issue of uncertainty is addressed by applying EMA. EMA can be contrasted with the use of models to predict system behavior, where models are built by consolidating known facts into a single package (Hodges and Dewar 1992). When experimentally validated, this single model can be used for analysis as a surrogate for the actual system. Where applicable, this consolidative methodology is a powerful technique for understanding the behavior of complex systems. Unfortunately, for many systems of interest, the construction of a model that may be validly used as surrogate is simply not a possibility. This may be due to a variety of factors, including the infeasibility of critical experiments, impossibility of accurate measurements or observations, immaturity of theory, openness of the system to unpredictable outside perturbations, or nonlinearity of system behavior, but is fundamentally a matter of not knowing enough to make predictions (Cambell et al. 1985, Hodges and Dewar 1992). For such systems, a methodology based on consolidating all known information into a single model and using it to make best estimate predictions can be highly misleading.

EMA can be useful when relevant information exists that can be exploited by building models, but where this information is insufficient to specify a single model that accurately describes system behavior. In this circumstance, models can be constructed that are consistent with the available information, but such models are not unique. Rather than specifying a single model and falsely treating it as a reliable image of the system of interest, the available information is consistent with a set of models, whose implications for potential decisions may be quite diverse. A single model run drawn from this potentially infinite set of plausible models is not a "prediction"; rather, it provides a computational experiment that reveals how the world would behave if the various guesses any particular model makes about the various unresolvable uncertainties were correct. By conducting many such computational experiments, one can explore the implications of the various guesses. EMA is the explicit representation of the set of plausible models, the process of exploiting the information contained in such a set through a large number of computational experiments, and the analysis of the results of these experiments. In this way, EMA aims at offering support to decision making, without falling into the pitfall of trying to predict the unpredictable.

EMA is not focused narrowly on optimizing a (complex) system to accomplish a particular goal or answer a specific question, but can be used to address 'beyond what if' questions, such as "Under what circumstances would this policy do well? Under what circumstances would it likely fail?" It is exceptionally valuable in stimulating 'out of the box' thinking and supporting the development of adaptive plans. EMA is first and foremost an alternative way of using models, knowledge, data, and information. Many well established techniques, such as Monte Carlo sampling, factorial methods, and optimization techniques, can be usefully and successfully employed in the context of EMA (Miller 1998, Agusdinata 2008, Kwakkel 2010).

3 Case

3.1 ANEMI

ANEMI, an ancient Greek term for the four winds, heralds of the four seasons, links physical systems such as climate, the hydrological cycle and the carbon cycle with socio-economic systems, including economy, land use, population change and water use (Davies and Simonovic 2010). It was designed as an integrated assessment model that would permit the assessment both of socio-economic policies and uncertainties about the overall system (Davies and Simonovic 2010). ANEMI is a system dynamics model, focusing in particular on the importance of the feedback relations between the various physical and socio-economic subsystems, and the dynamics arising out of these feedbacks, rather than aiming at providing detailed predictions.

ANEMI is a system dynamics model. Central to system dynamics models is the endogenous point of view (Richardson 2011). According to this view, the dynamic behavior of a system arises within the internal structure of a model. This view implies a closed system boundary, where the behavioral dynamics of the system arise out of interacting feedback loops. Thus, in system dynamics, a system is viewed as an ongoing interdepended, self-sustaining, dynamic process. That is, the observed behavior of a system is to be understood as arising out of the internal structure of the system. This internal structure of a system is conceptualized using stocks and flows, and relations between them. System dynamics is a modeling method for understanding the behaviors of nonlinear, dynamic and complex systems and for policy analysis and design (Sterman 2000).

ANEMI is composed of nine subsystems: climate, carbon cycle, economy, land-use, population, agricultural production, natural hydrological cycle, water use, and water quality (Davies 2007, Davies and Simonovic 2008, Davies and Simonovic 2011). Fig. 1 shows the main feedback structure of the model. The positive or negative sign associated with each arrow indicates the direction of change one model component has on the other model component. The names next to each arrow indicate which aspect of the model component causes a change in the other model component. The closed loop structure of the model implies that model behavior emerges endogenous feedbacks (Davies and Simonovic 2010). The model has been validated through comparison with government statistics, scientific data, results from other models, and socio economic data (Davies 2007, Davies and Simonovic 2008, Davies and Simonovic 2010, Davies and Simonovic 2011).

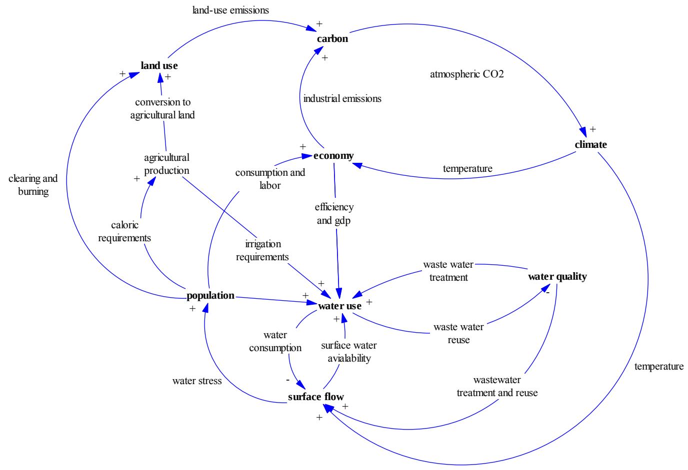

Fig. 1. Model components and their feedbacks (Davies and Simonovic 2011)

The climate sector is an upwelling diffusion energy balance model based on the box advection diffusion model of Harvey and Schneider (1985). The carbon cycle is based on Goudriaan and Ketner (1984), where the oceanic sector is modified based on Fiddaman (1997). The land use system is based on Goudriaan and Ketner (1984). The population component is based on Nordhause and Boyer (2000) and Fiddaman (1997). However, the dynamics are endogenous by including water stress (Davies and Simonovic 2010). The economic components is inspired by the updated DICE model (Nordhaus 2008). The three water parts and the agricultural production are unique to ANEMI, but build on earlier work (e.g. Shiklomanov 2000, Simonovic 2002). The water use model is similar to WaterGAP 2 (Alcomo et al. 2003). Water quality is comparable to how it is handled in WorldWater (Simonovic 2002). Surface flow, and the hydrological cycle are influenced by Chanine (1992), Shiklomanov (2000), and Simonovic (2002). The agricultural component is the latest addition to ANEMI and is based on Bouwman et al. (2005), Siebert and Döll (2010), and FAO data (Davies and Simonovic 2011).

3.2 Experimental design

Table 1 contains an overview of the parameters and their ranges that are to be explored. For this paper, we concentrated on parameters related directly to water use. The documentation of the model was reviewed and parameters that were either explicitly denoted as a guess or assumption, or for which divergent possible values were named were included in the analysis. The parameters include various time series that describe developments over the full runtime, such as the changing demand for food per person per year. These time series were replaced with sigmoid functions:

$$f(t) = \alpha \frac{1}{1 + e^{\frac{t-\tau}{s}}} + \beta$$

Here, α, β, γ, δ, are uncertain parameters that can be explored; α and β control the upper and lower limit of the sigmoid, γ controls when the sigmoid is half way between the two limits, and δ controls the slope.

Table 1. The uncertainties and their ranges

uncertainty	description	range
Agricultural Blue Water Dilution Factor	factor for dilution of polluted agricultural blue water	5-10
Agricultural Polluted Fraction	percentage of return flow of agricultural blue water that is polluted	0.7-0.95
Average Virtual Water Content of Crops	virtual water in crops in m3/Gcal	400-500
Average Virtual Water Content of Fodder	virtual water in fodder in m3/Gcal	200-300
Base Specific Water Intake	base value for water intake in agriculture in m3/ha/year	9000-12000
Base Returnable Water	base value for water return flow from agriculture in m3/ha/year	10-50
Base Precipitation Multiplier	increase of precipitation due to increasing global temperature in %/Celsius	3-4
Domestic Dilution Factor	factor for dilution of polluted domestic water	5-10
Domestic Polluted Fraction	percentage of return flow of domestic water that is polluted	90-100
Fractional Usage of Desalination Capacity	fraction of desalinization capacity that is being used	0.3-0.7
Fcl	simple area weighted cloud fraction	0.5-0.6
Gamma d	factor affecting increase in water demand per person due to gdp/capita increase	2.2e-10-2.2e-06
Industrial Dilution Factor	factor for dilution of polluted industrial water	5-10
Industrial Polluted Fraction	percentage of return flow of industrial water that is polluted	38-46
Max Groundwater Withdrawal	maximum amount of ground water withdrawal in km3/Year	7-10
Maximum Establishment of Desalination Facilities	maximum amount of desalinization capacity in km3/year	25-40
Percent Domestic Withdrawal	percentage of domestic withdrawal that is consumed	80-90
Stable and Useable Runoff Percentage	fraction of runoff that can be used, taking pollution dilution into account	30-40
Yield Ratio for rainfed to irrigated agriculture	yield fraction of rain fed agriculture as compared to irrigated agriculture	0.4-0.8
Wastewater Dilution Requirement	multiplier for dilution of polluted water	6-10
Technological Change for Consumption in Agricultural Sector lookup	transient scenario for technological change in agriculture affecting water consumption	sigmoid function
Technological Change for Withdrawals in Agricultural Sector lookup	transient scenario for technological change in agriculture affecting water withdrawal	sigmoid function
Crop Productivity Gains lookup	transient scenario for gains in crop productivity	sigmoid function

Percentage increase in irrigated area lookup	transient scenario for increase in irrigated area	sigmoid function
Global Per Capita Food Consumption lookup	transient scenario for increase in food consumption	sigmoid function

In order to explore the behavior of the model over the listed uncertainties, a shell written in Python is utilized. This 'EMA workbench' controls Vensim through its Dynamic Link Library (DLL). The workbench is responsible for generating input values for the various uncertainties, setting these values on the models, executing the models, and storing its results. The workbench supports parallel processing to reduce computational time. We used a Latin hypercube to generate 10.000 experiments. These were run on an pc with an Intel Xeon processer with six cores. Computational time was roughly 12 hours with 6 parallel processes.

3.3 Results

Fig. 2**Error! Reference source not found.** shows a performance envelope for three key performance indicators and a Gaussian kernel density estimate of the terminal values. We observe that over the 5.000 experiments, the water stress first rises and then either stabilizes or comes back down again. With respect to population, we observe that the population in 2100 can be somewhere between 10.000 and 16.0000 million. We also see that the blue water consumption in some of the runs exceeds the 4000 km^3 per year threshold suggested by Röckstrom et al. (2009). This raises the question how and why, despite crossing the suggested threshold, the water stress does not rise much above 0.5.

Water stress is affected by the amount of available surface water and the amount of water withdrawal, taking into account dilution of polluted water streams. Its main impact is on the growth rate of the world population. Fig. 3 shows the relative size and change of the flows in the world water cycle. It shows how miniscule human withdrawal is as compared to the other flows. Although human withdrawal increases somewhere between 100% and 700%, this growth still means that the human withdrawal, at a global scale, is quite small as compared to the flow from land to oceans and groundwater combined. The main driver for the change in the various flows is climate change. Climate change affects the evaporation of ocean water, in turn resulting in a change in precipitation.

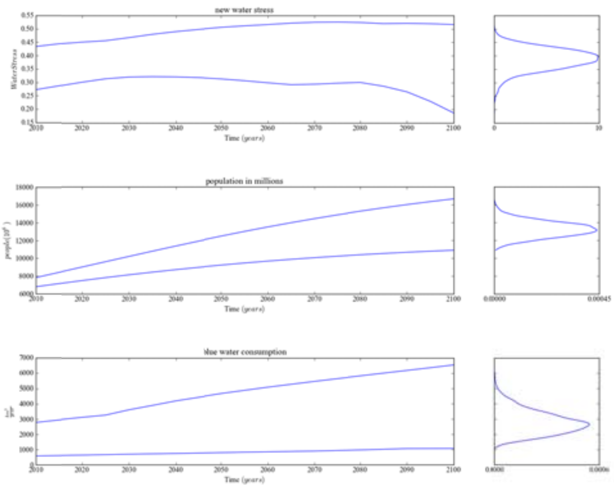

Fig. 2. Performance envelopes and end state Gaussian kernel density estimates

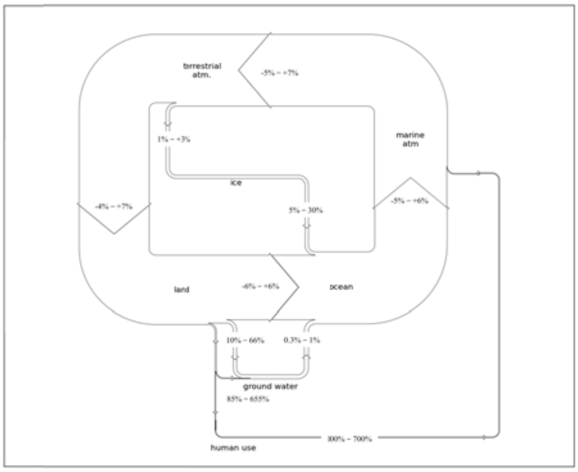

Fig. 3. The world water cycle and the expected change in relative size of the various flows taking climate change into account. The size of the arrows are approximately to scale. Note that human use does not take the dilution because of pollution into account

4 Discussion

The model considered in this paper is an integrated dynamic model of the world water cycle, taking into consideration the climate system, the population system, the economic system etc. However, this integration comes at the price of being not geographically and temporally explicit. Thus, changes in geographic precipitation patterns or shifts in the seasonal rain patterns are not included in this model. Even though the results indicate that the magnitude of the global hydrological cycles is massive as compared to human water use and that sufficient water is available at a global scale, this does not mean that there can be and are severe impacts on a river basin level due to spatiotemporal shifts in precipitation. That is, Molden's (2009) contention that it is potentially misleading to look at global limits for fresh water is corroborated by our results. For, in some of our simulations, the blue water consumptions per year passed the suggested threshold without resulting in catastrophic shifts in global dynamics. Still, given that values for water stress beyond 0.4 are seen as severe water stress (Alcomo, Flörke and Märker 2007), our results do indicate that water shortages are to be expected in the coming years.

The results also have methodological implications. They highlight how it is possible to account for model related uncertainties and assessing their implications on the type of dynamic the model produces. Limits to the planetary fresh water are shrouded in a myriad of uncertainties. However, this does not preclude the potential to shed some light on where these limits are roughly located, what type of dynamic behavior results in passing these limits and how the estimated values for such limits are conditioned on the uncertainty. A further analysis of the results from the computational experiments can help in clarifying which combinations of uncertainties are responsible for high values for water stress or low terminal values for the world population. Thus, instead of focusing on one, or a few runs from a model, we can systematically explore which dynamics the model can produce and the conditions under which these dynamics manifest themselves.

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