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Water footprint scenarios for 2050: A global analysis

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ABSTRACT

This study develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bioenergy use) and technological development. The objective the study is to understand the changes in the water footprint (WF) of production and consumption for possible futures by region and to elaborate the main drivers of this change. In addition, we assess virtual water flows between the regions of the world to show dependencies of regions on water resources in other regions under different possible futures. We constructed four scenarios, along two axes, representing two key dimensions of uncertainty: globalization versus regional selfsufficiency, and economy-driven development versus development driven by social and environmental objectives. The study shows how different drivers will change the level of water consumption and pollution globally in 2050. The presented scenarios can form a basis for a further assessment of how humanity can mitigate future freshwater scarcity. We showed with this study that reducing humanity's water footprint to sustainable levels is possible even with increasing populations, provided that consumption patterns change. This study can help to guide corrective policies at both national and international levels, and to set priorities for the years ahead in order to achieve sustainable and equitable use of the world's fresh water resources.
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1. Introduction

Competition over freshwater resources has been increasing during decades due to a growing population, economic growth, increased demand for agricultural products for both food and non-food use, and a shift in consumption patterns towards more meat and sugar based products (De Fraiture and Wichelns, 2010; Falkenmark et al., 2009; Shen et al., 2008; Strzepek and Boehlert, 2010). It looks like today's problems related to freshwater scarcity and pollution will be aggravated in the future due to a significant increase in demand for water and a decrease in availability and quality. Many authors have estimated that our dependency on water resources will increase significantly in the future and this brings problems for future food security and environmental sustainability (Alcamo et al., 2003a; Bruinsma, 2003, 2009; Rosegrant et al., 2002, 2009). A recent report estimates that global water withdrawal will grow from 4500 billion m^3/year today to 6900 billion m^3/year by 2030 (McKinsey, 2009).

Scenario analysis is a tool to explore the long-term future of complex socio-ecological systems under uncertain conditions. This method can and indeed has been used to assess possible changes to global water supply and demand. Such studies have been an interest not only of scientists but also of governmental agencies, businesses, investors and the public at large. Many reports have been published to assess the future status of water resources since the 1970s (Falkenmark and Lindh, 1976; Kalinin and Bykov, 1969; Korzun et al., 1978; L'vovich, 1979; Madsen et al., 1973; Schneider, 1976). Water scenario studies address changes in future water availability and/or changes in future water demand. Some of the recent scenario studies focused on potential impacts of climate change and socio-economic changes on water availability (e.g. Arnell, 1996, 2004; Fung et al., 2011; Milly et al., 2005). Other scenario studies also included the changes in water demand (Alcamo et al., 1996, 2000, 2003a,b, 2007; Rosegrant et al., 2002, 2003; Seckler, 1998; Shiklomanov, 2000; Vörösmarty et al., 2000). Change in water footprints per dietary preference in Europe is recently addressed by Vanham et al.(2013).

The major factors that will affect the future of global water resources are: population growth, economic growth, changes in production and trade patterns, increasing competition over water because of increased demands for domestic, industrial and agricultural purposes and the way in which different sectors of society will respond to increasing water scarcity and pollution. These factors are also mentioned in *Global Water Futures 2050*, a preparatory study on how to construct the upcoming generation of water scenarios by UNESCO and the United Nations World Water Assessment Program (Cosgrove and Cosgrove, 2012; Gallopín, 2012). In this study, ten different drivers of change are identified as critical to assess water resources in the long-term future: demography, economy, technology, water stocks, water infrastructure, climate, social behavior, policy, environment and governance.

In this study, we focus on water demand scenarios. In Table 1, we compare the scope of the current study with other recent water demand scenario studies. Vörösmarty et al. (2000) estimated agricultural, industrial and domestic water withdrawal for 2025, distinguishing single

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Table 1
Comparison of existing global water demand scenarios with the current study.

Study	Study characteristics	Sectoral disaggregation	Drivers used to estimate future water demand (no. of trajectories distinguished)
Vörösmarty et al. (2000)	Time horizon: 2025 Spatial scale: 30′ grid resolution Scenarios: 1 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Shiklomanov (2000)	Time horizon: 2025 Spatial scale: 26 regions Scenarios: 1 Scope: Blue water withdrawal and consumption	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Rosegrant et al. (2002, 2003)	Time horizon: 2025 Spatial scale: 69 river basins Scenarios: 3 Scope: blue water withdrawal and consumption	Agriculture: 16 sub-sectors Industry Domestic	Population growth (1) Urbanization (1) Economic growth (1) Technology change (3) Policies (3) Water availability constraints (3)
Alcamo et al. (2003a)	Time horizon: 2025 Spatial scale: 0.5° spatial resolution Scenarios: 1 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Alcamo et al. (2007)	Time horizon: 2025/2055/2075 Spatial scale: 0.5° spatial resolution Scenarios: 2 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (2) Economic growth (2) Technology change (1)
Shen et al. (2008)	Time horizon: 2020/2050/2070 Spatial scale: 9 regions Scenarios: 4 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (4) Economic growth (4) Technology change (4)
De Fraiture and Wichelns (2010)	Time horizon: 2050 Spatial scale: 115 socio-economic units Scenarios: 4 Scope: green and blue water consumption	Agriculture: 7 sub-sectors Industry: 2 sub-sectors Domestic	Population growth (1) Economic growth (1) Production and trade patterns change (4) Technology change (4) Consumption patterns—diet (1)
Current study	Time horizon: 2050 Spatial scale: 227 countries, 16 regions Scenarios: 4 Scope: green and blue water consumption, pollution as gray water footprint	Agriculture: 20 sub-sectors Industry Domestic	Population growth (3) Economic growth (4) Production and trade patterns change (4) Technology change (2) Consumption patterns—diets (2) Consumption patterns—biofuel (3)

trajectories for population growth, economic development and change in water use-efficiency. Shiklomanov (2000) assessed water withdrawals and water consumption for 26 regions of the world for the year 2025. Another global water scenario study was undertaken by Rosegrant et al. (2002, 2003), who addressed global water and food security for the year 2025. Compared to other recent studies, their study includes the most extensive list of drivers of change: population growth, urbanization, economic growth, technology change, policies and water availability constraints. Alcamo et al. (2003a) analyzed the change in water withdrawals for future business-as-usual conditions in 2025 under the assumption that current trends in population, economy and technology continue. A more recent assessment by Alcamo et al. (2007) improved their previous study by distinguishing two alternative trajectories for population and economic growth, based on the A2 and B2 scenarios of the IPCC for the years 2025, 2055 and 2075. Shen et al. (2008) studied changes in water withdrawals in the agricultural, industrial and domestic sectors for the years 2020, 2050 and 2070. One of the most extensive water demand scenario studies was done by De Fraiture et al. (2007) and De Fraiture and Wichelns (2010). These studies focused on alternative strategies for meeting increased demands for water and food in 2050. They elaborated possible alternatives under four scenarios for 115 socio-economic units (countries and country groups). None of the global scenario studies addressed the question of how alternative consumer choices influence the future status of the water resources except Rosegrant et al. (2002, 2003). In addition, the links between trends in consumption, trade, social and economic development have not yet been fully integrated.

The current study develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bio-energy use) and technological development. It goes beyond the previous global water demand scenario studies by a combination of factors: (i) it addresses blue and green water consumption instead of blue water withdrawal volumes; (ii) it considers water pollution in terms of the gray water footprint; (iii) it analyses agricultural, domestic as well as industrial water consumption; (iv) it disaggregates consumption along major commodity groups; and (v) it integrates all major critical drivers of change under a single, consistent framework. In particular, integrating all critical drivers is crucial to define policies for wise water governance and to help policy makers to understand the long-term consequences of their decisions across political and administrative boundaries.

We have chosen in this study to look at water footprint scenarios, not at water withdrawal scenarios as done in most of the previous studies. We explicitly distinguish between the green, blue and gray water footprints. The green water footprint refers to the consumptive use of rainwater stored in the soil. The blue water footprint refers to the consumptive use of ground or surface water. The gray water footprint refers to the amount of water contamination and is measured as the volume of water required to assimilate pollutants from human activities (Hoekstra et al., 2011).

The objective of the study is to understand the changes in the water footprint of production and consumption for possible futures by region and to elaborate the main drivers of this change. In addition, we assess virtual water flows between the regions of the world to show dependencies of regions on water resources in other regions under different possible futures.

2. Method

2.1. Scenario description

For constructing water footprint scenarios, we make use of global scenario exercises of the recent past as much as possible. This brings two main advantages: building our scenarios on well-documented possible futures and providing readers quick orientation of the storylines. As a starting point, we used the 2 × 2 matrix system of scenarios developed by the IPCC (Nakicenovic et al., 2000). These scenarios are structured along two axes, representing two key dimensions of uncertainty: globalization versus regional self-sufficiency, and economy-driven development versus development driven by social and environmental objectives. The two axes create four quadrants, each of which represents

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