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Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study

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ABSTRACT

To enhance global water use assessment, the WaterGAP3 model was improved for back-calculating domestic, manufacturing and thermoelectric water uses until 1950 for 177 countries. Model simulations were carried-out on a national scale to estimate water withdrawals and consumption as well as cooling water required for industrial processes and electricity production. Additionally, the amount of treated and untreated wastewater as generated by the domestic and manufacturing sectors was modeled. In the view of data availability, model simulations are based on key socio-economic driving forces and thermal electricity production. Technological change rates were derived from statistical records in order to consider developments in water use efficiency, which turned out to have a crucial role in water use dynamics. Simulated domestic and industrial water uses increased from ca. 300 km^3 in 1950 to 1345 km^3 in 2010, 12% of which were consumed and 88% of which were discharged back into freshwater bodies. The amount of domestic and manufacturing wastewater increased considerably over the last decade, but only half of it was untreated. The downscaling of the untreated wastewater volume to river basin scale indicates a matter of concern in East and Southeast Asia, Northern Africa, and Eastern and Southern Europe. In order to reach the Millennium Development Goals, securing water supply and the reduction of untreated wastewater discharges should be amongst the priority actions to be undertaken. Population growth and increased prosperity have led to increasing water demands. However, societal and political transformation processes as well as policy regulations resulting in new water-saving technologies and improvements counteract this development by slowing down and even reducing global domestic and industrial water uses.

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1. Introduction

Freshwater is abstracted for crop and energy production, industrial fabrication as well as human and ecosystem needs. According to the AQUASTAT database (FAO, 2010), 3856 km^3 of freshwater were withdrawn for domestic, industrial and agricultural purposes globally around the year 2003. Most of it was used in the agricultural sector (70%) followed by the industry (19%) and domestic (11%) sectors. The amount of water used varies between sectors and thus essentially determines the water use profile of a country or region, i.e. indicating the key water users within a certain area or region. For example, 82% of the water withdrawn in Asia is used by agriculture, while only 9% are attributed to the industry and domestic sectors. On the contrary, in Europe most of the water is used for industrial activities (55%) followed by the agricultural (29%) and domestic sectors (16%). Besides the water use profile, also the amount of water used varies enormously between regions and countries. For instance, regional estimates of total annual water withdrawals amount to 2451 km^3 or 642 m^3 per capita in Asia but only to 374 km^3 or 82 m^3 per capita in Europe (FAO, 2010).

Many historical records on domestic and industrial water use are discontinuous, incomplete, or non-existent. Up to now the most prominent global assessment of water resources of the 20th century was published by Shiklomanov and Rodda (2003) for 26 regions and selected countries based on literature review and statistical surveys. Among others, this includes information on water withdrawals and consumption. Another global database with free access to water-related datasets, in particular sector-specific water withdrawals, is established at the Food and Agriculture Organization of the United Nations (FAO). However, comprehensive and consistent time series for all countries worldwide are still lacking. Gleick (1998) stated in the first volume of The World's Water report that data on water use are among the most sought. Gleick repeated this statement 13 years later (Showstack, 2011) and pointed out that an adequate data

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survey is vital for understanding how water is used in the U.S. It should be noted that the U.S.'s national water-use records go back till 1950 and were conducted every 5 years by the U.S. Geological Survey (USGS). Similarly, long-term time series are available in Germany (i.e. historical data for Western Germany) with triennial census results provided by the Statistisches Bundesamt (DESTATIS). Overall, data acquisition concerning a country's population or economy is standard but an area-wide and systematic data survey of sectoral water uses is still lacking, particularly in developing countries. Moreover, when it comes to the collection of water quality-related data, i.e. wastewater volumes, loadings, and concentrations, the situation is even worse. Domestic and industrial effluents are major sources of water quality degradation. Large volumes of untreated (or inadequately treated) wastewater are still discharged into surface water and groundwater causing widespread water contamination and thermal pollution, intensification of health risks, and deterioration of aquatic ecosystems.

Water resource managers and planners require data on water uses, i.e. water withdrawals, return flow, and consumptive use (see Section 2 for definition) to understand how anthropogenic water use affects the hydrological system (Shaffer and Runkle, 2007; Showstack, 2011). The estimation of freshwater abstractions and consumption is of high interest for looking ahead but also when looking back into the past (Shiklomanov, 2000). How can we constructively think about future developments of water-related sectors if we do not know how water was used in the past? For example, information on water use together with the quantification of renewable water resources indicates hotspots of water stress (water scarcity) and their development over time. Nevertheless, even if agriculture is the dominating water consuming sector in many regions of the world, the domestic and industry sectors can also contribute to achieving a reduction of vulnerability to water stress. This requires that water-related policies are effectively mainstreamed into other sectoral policies such as for industry (in particular water saving in the energy sector), urban development, or tourism.

The applicability of a model to represent past and current conditions depends on precise input data. Limited or poor water-use data impede the ability of modelers to simulate these conditions. There are a number of large-scale models to simulate agricultural water requirements, in particular irrigation water requirements and their effects on water resources (Haddeland et al., 2007; Rost et al., 2008; Wisser et al., 2009; Sauer et al., 2010; Siebert et al., 2010; Supit et al., 2010; Aus der Beek et al., 2011). However, model simulations to estimate historical water uses in the domestic and industry sectors are still missing. So far, the global water model WaterGAP2 has been used to calculate current and future water withdrawals and consumption for different sectors (domestic, industry, and agriculture) on a global scale (Döll and Siebert, 2002; Alcamo et al., 2003). At first, water use simulations for the domestic and industry sectors were carried out based on a regional approach (Alcamo et al., 2003), then the industrial water uses were differentiated into manufacturing and thermoelectric water use for the year 1995 (Vassolo and Döll, 2005) followed by further model improvements applied for Europe (Flörke and Alcamo, 2004; Flörke et al., 2012).

In this paper, we describe further methodological improvements to simulate global water use in the domestic, manufacturing, and thermoelectric sectors as implemented in WaterGAP3, which are now possible for more than 170 countries covering the time period 1950–2010. WaterGAP has been applied to project sectoral water uses in many studies (e.g. MA, 2005; Alcamo et al., 2007; Flörke et al., 2011; Schaldach et al., 2012) but has not yet been tested through hindcasting. Hindcasting is a technique to evaluate model outcomes including the ability to identify turning points and events (Clark et al., 2001), which is important for communicating model uncertainty. The model results obtained in this study are discussed and compared to historical and current datasets on different scales (global, regional, and national). As we determine the amount of sectoral water discharged back into freshwater bodies, we are able to present estimates of treated and untreated return flows from the domestic and industrial sectors for the years 2000–2010. Since spatially explicit information is also important, e.g. for visualizing industrialization and urbanization or identifying hotspots, the model computes the results on a $5' \times 5'$ grid, which can be aggregated to sub-national (e.g. NUTS-2 or counties) or river basin scales.

2. Methods and data

The global Water Use model of WaterGAP was designed to estimate current and future water withdrawals and consumption of the domestic, industrial, and agricultural sectors. In its current version, the Water Use model consists of five different sub-models covering the domestic, manufacturing, thermal electricity production, irrigation, and livestock sectors. The paper focuses on modeling water uses for domestic, manufacturing, and thermal electricity production purposes over the past 60 years in order to fill the information gap identified in the previous chapter.

The water-related terms follow the definitions used by the U.S. Geological Survey (Shaffer and Runkle, 2007): *Water use* – refers to the volume of water that is used for a specific purpose. It is partitioned into water withdrawal, consumption, and return flows. *Water withdrawal* – the volume of water abstracted from either a surface water or groundwater source. In general, information on measured water withdrawals is widespread and publicly available from different sources, e.g. international and national statistics, or reported in the literature. *Water consumption* – the share of water withdrawal that is evaporated, transpired, incorporated into products or crops, or consumed by humans. Two methods are commonly used to estimate water consumption: (i) using a balancing equation and (ii) using consumptive-uses coefficients (Shaffer and Runkle, 2007). Information about water consumption is rather scarce with only few available reports (Shiklomanov and Rodda, 2003; Statistics Canada, 2005; Shaffer and Runkle, 2007). *Return flow* – water that reaches a groundwater or surface water body after release from the point of use, thus becoming available for further use. Return flow can be regarded as the difference between water withdrawal and water consumption.

2.1. The domestic water use model

The domestic water use sub-model calculates the annual water withdrawals and consumption of households and small businesses for 177 countries worldwide. The basic approach is to compute the domestic water use intensity (m^3 capita^{-1} year^{-1}), which is then multiplied by population. Changes in water use intensity are expressed as structural changes and technological changes (Alcamo et al., 2003; Flörke and Alcamo, 2004). The concept of structural change is based on the observation that, as average income increases, water users at first tend toward a more water-intensive lifestyle. Eventually, after a maximum level is reached, per capita water use is either stable or declines. Structural change is represented by a sigmoid curve which indicates how water use intensity changes with income (GDP per capita) (Fig. 1). The current model version builds upon this following an improved methodology. Instead of using solely regional curves to estimate past and future domestic structural water use intensities (DSWI), the relationship between water use intensity and income is now derived for 50 individual countries (e.g. Fig. 1a). Where data availability is poor (e.g. African countries, islands in the Pacific and Indian Ocean) the available information is combined in order to

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