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Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydro-climatic variability

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ABSTRACT

Changes in available fresh water resources, together with changes in water use, force our society to adapt continuously to water scarcity conditions. Although several studies assess the role of long-term climate change and socioeconomic developments on global water scarcity, the impact of inter-annual climate variability is less understood and often neglected. This paper presents a global scale water scarcity assessment that accounts for both temporal changes in socioeconomic conditions and hydro-climatic variability over the period 1960–2000. We thereby visualized for the first time possible over- and underestimations that may have been made in previous water scarcity assessments due to the use long-term means in their analyses. Subsequently, we quantified the relative contribution of hydro-climatic variability and socioeconomic developments on changing water scarcity conditions. We found that hydro-climatic variability and socioeconomic changes interact and that they can strengthen or attenuate each other, both regionally and at the global scale. In general, hydro-climatic variability can be held responsible for the largest share (>79%) of the yearly changes in global water scarcity, whilst only after six to ten years, socioeconomic developments become the largest driver of change. Moreover, our results showed that the growth in the relative contribution of socioeconomic developments to changing water scarcity conditions stabilizes towards 2000 and that the impacts of hydro-climatic variability remain significantly important. The findings presented in this paper could be of use for water managers and policy makers coping with water scarcity issues since correct information both on the current situation and regarding the relative contribution of different mechanisms shaping future conditions is key to successful adaptation and risk reduction.

1. Introduction

Globally, water scarcity and its societal consequences is recognized as one of the most important global risks, both in terms of likelihood and impact (Howell, 2013). Governments and institutions managing water resources have to adapt constantly to regional water scarcity conditions, which are driven by climate change, climate variability, and changing socioeconomic conditions. Over the past decades, changing hydro-climatic and socioeconomic conditions increased regional and global water scarcity problems (Kummu et al., 2010; Vorosmarty et al., 2000; Wada et al., 2011a,b). Future climate change, projected population growth, and the continuing increase in water demand, are expected to aggravate these water scarcity conditions world-wide (Alcamo et al., 2007; Haddeland et al., 2014; Kiguchi et al., 2015; Lehner et al., 2006; Prudhomme et al., 2014; Schewe et al., 2014; Sperna Weiland et al., 2012; Stahl, 2001; Van Vliet et al., 2013; Wada et al., 2011a).

Whilst most research on water scarcity has focused on the role of long term changes in hydro-climatic and socioeconomic conditions, the role of inter-annual hydro-climatic variability has received less attention. This is problematic, since variability has been identified as a key theme for water scarcity assessments (e.g. Mason and Calow, 2012), and changes in variability may be

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more important than changes in average conditions when examining extreme events, such as flood and droughts, in a changing climate (Adger et al., 2005; Hall and Borgomeo, 2013; IPCC, 2012; Katz and Brown, 1992; Mason and Calow, 2012; Smit and Pilifosova, 2003). Omitting the climate-driven inter-annual variability in water resources availability (i.e. hydro-climatic variability) can mean that areas that only sporadically experience water scarcity are overlooked. On the other hand, those areas that are identified as 'water scarce' based on hydro-climatic mean conditions, in reality do not experience water scarcity every year (Kummu et al., 2014; Mason and Calow, 2012). Likewise, studies using such multi-year averages, either with respect to hydro-climatic or socioeconomic conditions, might misinterpret the relative contribution of these driving forces on changing water scarcity conditions towards the future (Hulme et al., 1999; Kummu et al., 2014; McPhaden et al., 2006; Murphy et al., 2010; Seneviratne et al., 2012; Vera et al., 2010). Moreover, earlier research showed that the adaptive capacity of people to gradually changing means is relatively high, whereas adapting to yearly variations and extremes poses more difficulties (Smit and Pilifosova, 2003). This holds especially for those regions that lack a minimum level of hydraulic infrastructure for water storage and redistribution (Grey and Sadoff, 2007; Hall and Borgomeo, 2013). A thorough understanding of the present-day contribution of inter-annual variability is essential to model future interactions between different driving forces and their impacts on future water scarcity conditions, and is therefore a prerequisite for successful adaptation (Adger et al., 2005; Hall and Borgomeo, 2013; Mason and Calow, 2012; Smit and Pilifosova, 2003).

To address the considerations discussed above, we present in this contribution a global scale water scarcity assessment that accounts for both temporal changes in socioeconomic conditions and hydro-climatic variability. A first effort to estimate the effects of hydro-climatic variability on water scarcity conditions at the global scale was made by Kummu et al. (2014). In this study, however, an assumption of fixed socioeconomic conditions was used, which may have led to an over- or underestimations of water scarcity conditions at the global and regional scale. Using a scenario analysis, we visualize here the size of these potential over- and underestimations. In addition, we quantify the relative impacts of these driving forces on changes in water scarcity, using a calculation method that takes into account their interaction effects and thereby avoids the risk of over- or underestimations as specified above. We conclude with a discussion on the implications of our results for water management and policy, for example in designing adaptation strategies.

2. Materials and methods

In brief, we constructed time-series of yearly water availability, using the multi-model ensemble-mean of water availability derived from three global hydrological models. We then combined these water availability time-series with data on population and water consumption to calculate water scarcity conditions over the period 1960–2000 under four scenarios, representing fixed or transient socioeconomic and hydro-climatic conditions. Finally, we evaluated the differences in estimated water scarcity conditions, the severity of water scarcity events, and the (relative) contribution of different driving factors to changing water scarcity conditions. A cross-model validation was carried out to test the sensitivity of our results to the use of different global hydrological models. All analyses were carried out globally at the scale of Food Producing Units (FPU), which represent a hybrid between river basins and economic regions (Supplementary Fig. S7) (Cai and Rosegrant, 2002; De Fraiture, 2007; Rosegrant et al., 2002). Data and methods are described in detail in the following subsections. An overview of the steps taken in the methodology is given in Fig. 1.

2.1. Input data

2.1.1. Water availability scenarios

Monthly water availability was estimated over the period 1960–2000 using time-series of gridded ($0.5^\circ \times 0.5^\circ$) daily runoff and discharge from three global hydrological models: PCR-GLOBWB (Van Beek et al., 2011; Wada et al., 2014b), STREAM (Aerts et al., 1999; Ward et al., 2007) and WaterGAP (Müller Schmied et al., 2014). The three models were forced with daily precipitation and temperature data ($0.5^\circ \times 0.5^\circ$) from the EU-WATCH project (Weedon et al., 2011). For each of the models, we aggregated daily runoff values per grid-cell into time-series of monthly runoff per FPU: thereby calculating its monthly water availability. In large river basins, using total monthly runoff as a measure for water availability may lead to overestimations of the water actually available upstream, while it may lead to underestimations in the case of downstream areas (Supplementary Fig. S8). To account for this issue, we redistributed water availability across those FPUs located within a large river basin, proportionally to the basin's long-term average discharge distribution (Eq. (1)) (Gerten et al., 2011; Schewe et al., 2014). WA_i is here the redistributed monthly water availability within FPU i, R_b is the total monthly water availability within large river-basin b, Q_i is the long-term average monthly discharge in FPU i, and $\sum Q_i$ is the sum of the long-term average monthly discharge over all FPUs within large river-basin b.

$$WA_i = \frac{R_b * Q_i}{\sum Q_i} \tag{1}$$

Using the aggregated yearly water availability estimates per FPU from each of the three global hydrological models, we constructed a multi-model ensemble-mean time-series of water availability per FPU over the period 1960–2000, the time-period used in our analyses. To calculate water availability under fixed and fixed hydro-climatic conditions we used a long-term average climatology over the period 1960–2000, a period long enough to calculate average values which are not subjective to inter-annual variability (Döll et al., 2003).

2.1.2. Consumptive water use scenarios

We used time-series of monthly consumptive water use (hereafter: water consumption) produced by Wada et al. (2011b) in our calculations of global water scarcity conditions using the Consumption to Availability ratio (CTA-ratio, see Section 2.2). Monthly gridded water consumption ($0.5^\circ \times 0.5^\circ$) was estimated per sector (livestock, irrigation, industry and domestic) over the period 1960–2000 using CRU TS 2.1 temperature time-series combined with yearly information on: livestock densities; the extent of irrigated areas; desalinated water use; non-renewable groundwater abstractions; and past socioeconomic developments, namely GDP, energy and electricity production, household consumption, and population growth (Wada et al., 2011b). For a complete description and discussion of the water consumption calculation framework, we refer the reader to Wada et al. (2011a,b). In order to reflect the fixed socioeconomic conditions, 1960 was used as a benchmark year for the different water consuming sectors. Since the amount of water used for irrigation is, however, not only driven by socioeconomic developments but also by changing hydro-climatic conditions, we computed four time-series of irrigation water consumption (see also Table 1): irrigation under fixed conditions; irrigation under transient conditions; irrigation under fixed socioeconomic