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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.

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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 .

$$WA_i = \frac{R_b * Q_i}{\sum Q_i} \quad (1)$$

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

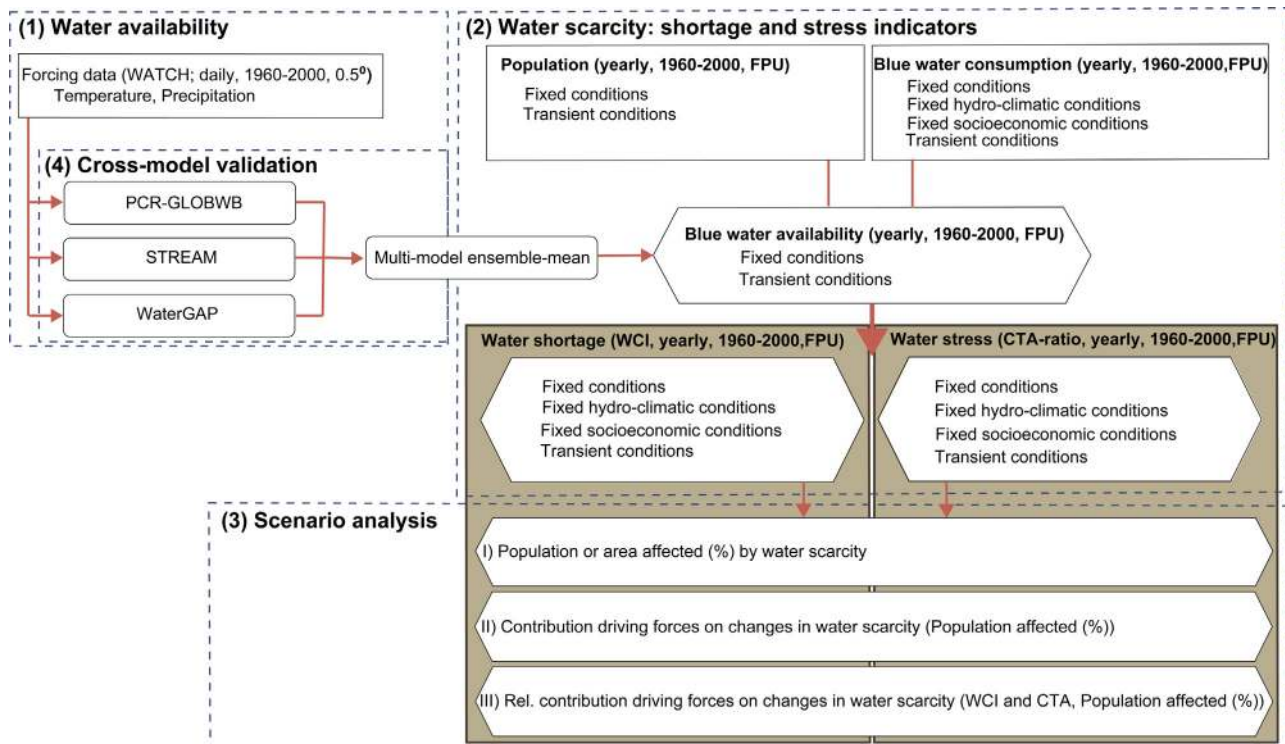


Fig. 1. Overview of the steps taken in the methodology. Squared boxes are input data; rounded boxes represent the global hydrological models used and the multi-model ensemble-mean time-series constructed; diamonds show (intermediate) results. In general, the methodology can be split into: (1) calculating water availability (Section 2.1.1); (2) calculating water scarcity conditions by means of the Water Crowding Index (WCI) and the Consumption to Availability ratio (CTA-ratio) (Section 2.2); (3) executing the scenario analysis (Section 2.3); and (4) executing the cross-model validation (Section 2.4). Fixed, fixed hydro-climatic, fixed socioeconomic, and transient conditions refer to the different conditions used in the scenario analysis and are elaborated further in Section 2.3 (Table 1).

conditions; and irrigation under fixed hydro-climatic conditions. Under fixed socioeconomic conditions only the socioeconomic conditions are fixed calculating the irrigation water consumption, hydro-climatic conditions were kept transient. Under fixed hydro-climatic conditions, we excluded hydro-climatic variability in water availability in combination with transient socioeconomic conditions to estimate irrigation water consumption. The gridded total monthly water consumption scenarios were aggregated into scenarios of yearly water consumption per FPU covering the period 1960–2000.

2.1.3. Population scenarios

The population data used for the calculation of global water scarcity using the Water Crowding Index (WCI) (Section 2.2) are equal to the population time-series used within the calculation of monthly water consumption by Wada et al. (2011b) (Section 2.1.2). Wada et al. (2011b) combined yearly country-scale population data from FAOSTAT with decadal global population maps (Klein Goldewijk and van Drecht, 2006) to derive yearly gridded population maps ($0.5^\circ \times 0.5^\circ$). We aggregated these population

maps into time-series of yearly population per FPU, with the year 1960 as benchmark year representing the fixed socioeconomic conditions.

2.2. Water scarcity indicators

Blue water scarcity (hereafter: water scarcity) refers to the imbalance between water availability (natural runoff) and the needs for water over a specific time period and for a certain region. Water scarcity can be population-driven, expressed as water available per person per year; or demand-driven, expressed as the actual consumed water by all sectors and people relative to the water available (Falkenmark, 2013a). Two complementary indicators often used to quantify these water scarcity conditions are the Water Crowding Index (WCI) and the Consumption to Availability ratio (CTA-ratio), respectively (Brown and Matlock, 2011; Falkenmark, 2013a; Rijsberman, 2006). The WCI quantifies the yearly water availability per capita at the country or basin-scale (Falkenmark, 1986, 2013a), also referred to as water shortage. In line with previous studies (e.g. Arnell, 2004; Kummur et al.,

Table 1

Four scenarios are used to quantify possible anomalies in water scarcity estimates.

Scenario	Water availability	Water consumption	Population
(1) Fixed	Fixed (long-term average climatology) ^a	Fixed ^b	Fixed ^b
(2) Fixed hydro-climatic	Fixed (long-term average climatology) ^a	Transient, except for irrigation ^c	Transient
(3) Fixed socioeconomic	Transient	Fixed, except for irrigation ^{b,c}	Fixed ^b
(4) Transient	Transient	Transient	Transient

^a The long-term average climatology over the period 1960–2000 was used to calculate water availability under fixed and fixed hydro-climatic conditions.

^b 1960 was used as a benchmark year for the calculation of yearly water consumption and population under fixed and fixed socioeconomic conditions.

^c Irrigation water demand is driven by both socioeconomic and hydro-climatic conditions. Under fixed socioeconomic conditions only the socioeconomic conditions are fixed calculating the irrigation water demand, hydro-climatic conditions were kept transient. Under fixed hydro-climatic conditions, we excluded hydro-climatic variability (by using long-term average climatology in water availability calculations) in water availability in combination with transient socioeconomic conditions to estimate irrigation water demand.

2010), we use the thresholds as defined by Falkenmark et al. (1989), Falkenmark (1986) and updated in Falkenmark (2013a): 1700 m³/capita per year as the threshold level below which water shortage events occur. The CTA-ratio examines how much water is consumed relative to the amount of water available in a specific region and has been applied in a wide range of studies to calculate water stress (Falkenmark, 2013a,b; Hoekstra et al., 2012; Kiguchi et al., 2015; Oki and Kanae, 2006; Vorosmarty et al., 2000; Wada et al., 2011a). Following these studies we applied a threshold level of 0.2 to indicate water stress events. While most of these studies tend to focus on only one of these water scarcity indicators, we studied both and in a consistent way, which limits us to a maximum resolution in space (FPU) and time (year). Eqs. (2) and (3) show the use of the Water Crowding Index ($WCI_{i,yr}$) and the Consumption to Availability ratio ($CTA_{i,yr}$), respectively. $WA_{i,yr}$ is here the water available per FPU i and year yr , $P_{i,yr}$ is the population per FPU i and year yr , and $C_{i,yr}$ is the water consumption per FPU i and year yr .

$$WCI_{i,yr} = \frac{WA_{i,yr}}{P_{i,yr}} \text{ (water shortage if } WCI_{i,yr} \leq 1700) \quad (2)$$

$$CTA_{i,yr} = \frac{C_{i,yr}}{WA_{i,yr}} \text{ (water stress if } CTA_{i,yr} \geq 0.2) \quad (3)$$

2.3. Scenario analysis: anomalies in water scarcity assessments

Excluding socioeconomic developments or hydro-climatic variability in water scarcity assessments can lead to over- and underestimations of the water scarcity conditions, the perceived severity of water scarcity events, and in a misinterpretation of the impact of their underlying driving forces. Four scenarios were used to quantify the size of these potential over- and underestimations, each of them built from a combination of fixed or transient socioeconomic and fixed or transient hydro-climatic conditions (Table 1).

2.3.1. Anomalies in water scarcity assessments

Global and regional annual anomalies in water scarcity and the severity of water scarcity events were quantified by comparing our water scarcity estimates, as found under the fixed hydro-climatic and fixed socioeconomic conditions, with the estimates derived under the transient conditions. The severity of water scarcity events was expressed here by means of percentages of the total population affected per region and anomalies were given in percentage-points (pp), see also the Supplementary Methods for a calculation example (Supplementary Methods, Example 1).

Subsequently, we quantified the size of possible over- and underestimations in the assessed contribution of driving forces on water scarcity estimates when being studied in an isolated manner. For that purpose, we estimated:

- (i) The total impact of these driving forces on changing water scarcity conditions and changes in the population affected by water scarcity events under the transient conditions, and relative to the fixed conditions (transient conditions);
- (ii) The summed impact of these driving forces studied in an isolated manner: summing the changes in water scarcity conditions and affected population as calculated under both the fixed hydro-climatic and the fixed socioeconomic conditions, and relative to the fixed conditions (summed conditions).

A comparison of the results for these summed and transient conditions resulted in estimates of the size of potential anomalies regarding the impact of underlying driving forces of changing

water scarcity conditions and its perceived severity. A calculation example is given in the Supplementary Methods (Example 2).

2.3.2. Relative contribution of driving forces on changing water scarcity conditions

Additionally, we assessed the relative contribution of the driving forces 'socioeconomic development' and 'hydro-climatic variability', expressed as percentages of the total actual change in water scarcity conditions. In doing so, we take into account the interaction effects of these individual driving forces and thereby overcome the risk of over- or underestimations. Similar to Section 2.3.1, we first calculated per FPU and per year the isolated impacts of changes in socioeconomic conditions and hydro-climatic variability on changing water scarcity conditions. Subsequently, we expressed the impacts of each of these driving forces as a percentage of the actual total cumulative and yearly change in water scarcity conditions over time. Results per FPU were aggregated to the scale of regions using a weighted summation based on population densities (see Supplementary Methods for a calculation example, Example 3). For water stress, we also assessed the relative contribution of the different water consuming sectors to the overall change in water scarcity conditions, a detailed description on these calculations can be found within the Supplementary Methods.

2.4. Cross-model validation

A cross-model validation was carried out to evaluate the sensitivity of our results to the choice of global hydrological model. For that purpose, we compared the multi-model ensemble-mean water availability time-series with the time-series of the three global hydrological models (PCR-GLOBWB, STREAM, and WaterGAP) individually. The main findings of this cross-model validation are discussed in the results and discussion section (Section 3.4), while the individual results are presented more extensively in Supplementary Cross-model validation.

3. Results and discussion

3.1. Water scarcity assessments under transient conditions

Globally, the population living in FPUs affected by water scarcity events increased over the period 1960–2000, both in absolute terms as well as relative to the total population (Fig. 2.A). Between 1960 and 2000, the population affected by water shortage rose from 473 million to 2.55 billion, whilst the population affected by water stress increased from 326 million to 1.9 billion. Relative to the total population, this represents an increase from 17% to 45% for water shortage, and from 11.7% to 33.6% for water stress. Over this period (1960–2000), 8.9–28.6% of the global population lived under both water shortage and stress conditions. Correcting for this observation, we found that the share of the global population living under some sort of water scarcity increased from 19.8% in 1960 up to 49.9% in 2000 under transient conditions. Fig. 2B distinguishes these three groups of water scarcity, and also shows the spatial differentiation in population affected (%) between different regions. As a result of the fact that some regions encounter both water shortage and stress, it is difficult to examine the relative contributions of climate variability and socioeconomic development to the overall changes. For that reason, we continued our analysis distinguishing only between water shortage and stress, thereby acknowledging the fact that we cannot sum the two numbers of the individual scarcity events to derive the total amount of people affected by water scarcity events.

The global results, and the regional distribution of water scarcity events under transient conditions, are similar to those

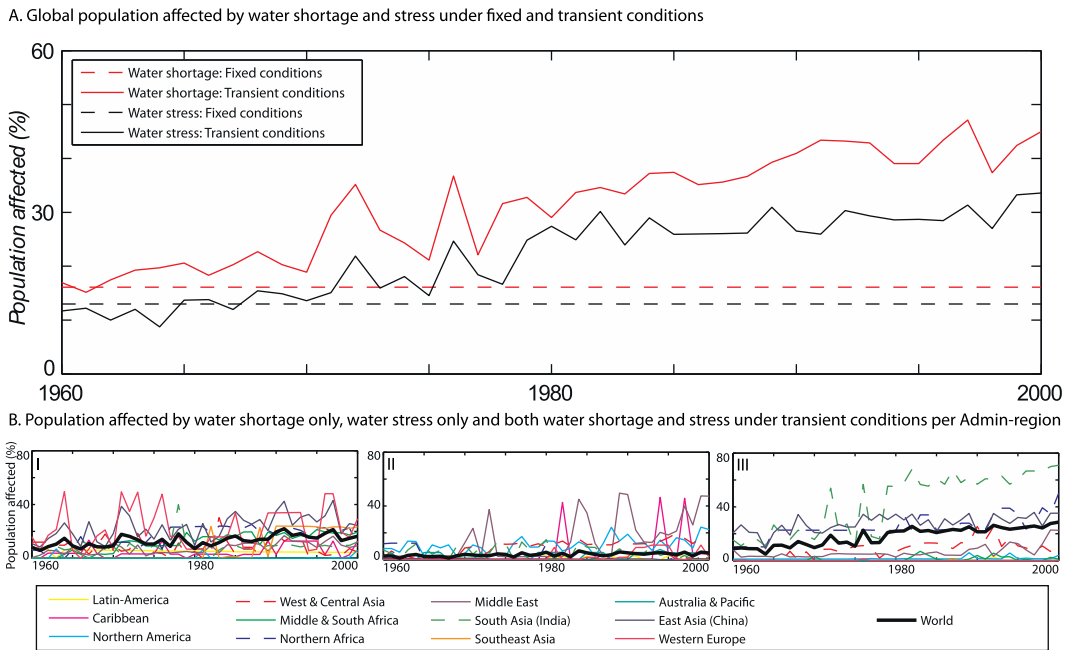


Fig. 2. Population affected by water scarcity under fixed and transient conditions. (A) The percentage of the global population affected by water shortage and stress under fixed or transient conditions. (B) Percentage of the population, globally and per world region, affected by: I. Water shortage only; II. Water stress only; and III. Both water shortage and stress at the same time.

found in previous studies (Wada et al., 2011a; Kummu et al., 2010). Kummu et al. (2010) calculated an increase in the population dealing with water shortage ($<1700 \text{ m}^3 \text{ cap}^{-1} \text{ yr}^{-1}$) from 19% in 1960, to 50% in 2005. Wada et al. (2011a) estimated an increase in the population affected by water stress ($\text{CTA} \geq 0.2$) from 10% in 1960 to 28% in 2000. Whilst the population living in the Middle East, Australia & Pacific, and parts of western North America are mainly affected by water stress, water shortage occurs predominantly in Western Europe and Africa. Asia, some African regions, and a few areas within Northern America, are affected by both water shortage and stress throughout the period 1960–2000. Supplementary Fig. S9 shows the spatial distribution of the

frequency of water scarcity events per FPU. The differences in the spatial distribution of the two water scarcity indices can be explained by regional differences in economic water demands and population density compared to the availability of water.

3.2. Anomalies in water scarcity assessments

Analyses carried out using either fixed socioeconomic conditions or excluding hydro-climatic variability omit possible interactions that can enhance or attenuate changes in water scarcity conditions. Fig. 3 shows the population affected at the global scale as calculated under fixed, transient, fixed socioeconomic, and fixed

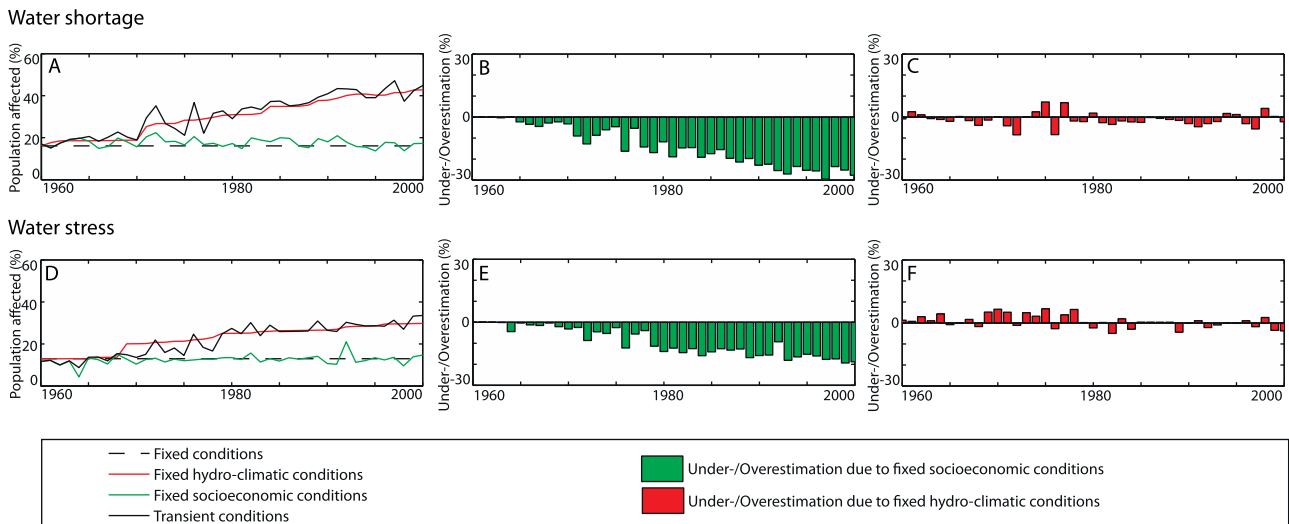


Fig. 3. Global scale over- and underestimations in the population affected by water shortage and stress events due to the use of fixed socioeconomic or hydro-climatic conditions in water scarcity assessments. (A and D) The population affected by water shortage and stress events respectively at the global scale, under fixed, fixed hydro-climatic, fixed socioeconomic or transient conditions. (B and E) The anomaly in population affected by water shortage and stress events respectively due to the use of fixed socioeconomic conditions in water scarcity assessment, expressed in percentage-points. (C and F) The anomaly in population affected by water shortage and stress events respectively due to the use of fixed hydro-climatic conditions in water scarcity assessment, expressed in percentage-points.

hydro-climatic conditions. Globally, the use of fixed socioeconomic conditions leads to an underestimation of the estimated population affected by water shortage by 29.5 percentage-points (pp) (Fig. 3B); for water stress the underestimation is by 19.4 pp (Fig. 3E). Even larger underestimations can be found regionally (Supplementary Fig. S10): up to 70.1 pp for water shortage (India) and 64.1 pp for water stress (Middle East). Compared to water scarcity assessments that include hydro-climatic variability, those using long-term average climatology lead to both over- and underestimations of the population affected, (Fig. 3C and F). Globally, these anomalies vary from underestimations of 7.2 and 5 pp for water shortage and stress respectively, up to overestimations of 8.5 (shortage) and 6.7 (stress) pp. Again, larger anomalies are found at the regional scale (Supplementary Fig. S10): for water shortage we found overestimations in the estimated population affected of 32.8 pp (Western Europe) and underestimations up to 42.6 pp (India). For water stress we found overestimations of affected population by up to 46.4 pp (Caribbean) and underestimations by up to 36.7 pp (India). Spatial and temporal differences in water consumption and population growth patterns cause spatial differences in water scarcity values and therefore form the basis of the differences in anomalies between regions and between the water scarcity indicators. A second explanation for the variations in the anomalies found, both spatially and between the two water scarcity indicators, is the use of threshold values in water scarcity assessments. By using these thresholds, small changes in water scarcity could result in relatively large changes in terms of population affected, and vice versa. Applying continuous water scarcity conditions, rather than using scarcity thresholds could help to resolve this issue. When repeating our analysis with continuous water scarcity conditions, we observe that the magnitude of the anomalies increases, both at the global and regional scales (Supplementary Figs. S11–S13).

Fig. 4 shows that if we simply sum the isolated impacts of changing socioeconomic conditions and hydro-climatic variability per year on water scarcity (water shortage or stress conditions),

this leads to over- or underestimations of the total change in scarcity. Globally, this yearly over- or underestimation ranges between -4.51 and $+1.95$ pp for water shortage, and between -0.75 and $+2.01$ pp for water stress. Regional over- and underestimations vary in size, frequency and sign (\pm) from the global aggregates (Supplementary Fig. S14). When comparing the two water scarcity indicators used, we find differences in results not only regarding the magnitude, but also with respect to the frequency and sign of anomalies found. These differences are for a large part caused by the initial conditions in population affected, the water scarcity conditions under the different scenarios, and the threshold levels applied. Therefore, we repeated the analysis using continuous water scarcity conditions, which results in higher over- and underestimations at both the global and regional scale for water shortage, and for a selection of regions for water stress (Supplementary Fig. S11–S13).

3.3. Relative contribution of driving forces on changing water scarcity levels

Subsequently, we expressed the relative contribution of (sectoral) socioeconomic changes and hydro-climatic variability on changes in water shortage and stress conditions. In doing so, we avoid the problems described in the previous section. We found that the relative contribution of socioeconomic change increases globally, from 0% (1960) up to 76.2% for water shortage, and 82.5% for water stress, which is the result of continuous population growth and accumulating consumptive water demands from 1960 onwards (Fig. 5A). Despite the accumulation of socioeconomic developments over time, however, the growth in the relative contribution of socioeconomic developments to changing in water scarcity conditions stabilizes towards 2000. Decreasing returns to scale can explain this observation: output (here: water scarcity levels) changes by less than the proportional change in inputs (here: socioeconomic changes). This implies that even after 40 years of accumulating socioeconomic developments, the impact of hydro-climatic variability on water scarcity remains important.

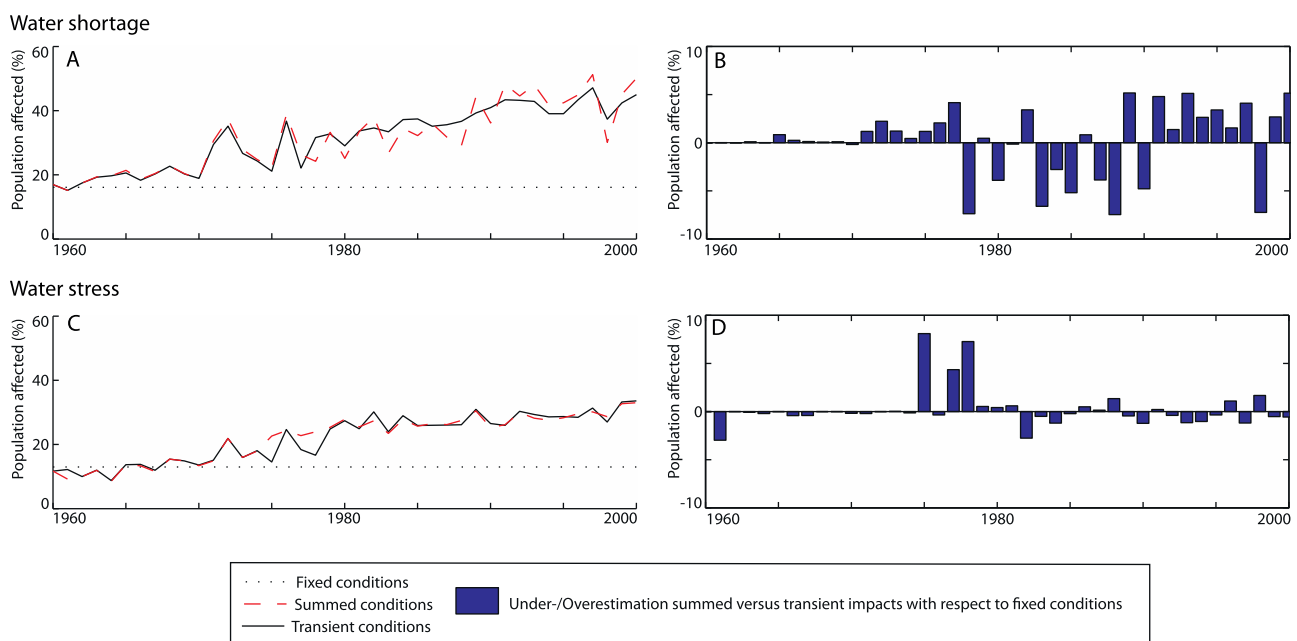


Fig. 4. Global scale over- and underestimations in the estimated impact of the driving forces 'changing socioeconomic conditions' and 'hydro-climatic variability' on changes in population affected by water scarcity due to the use of fixed socioeconomic or hydro-climatic conditions in water scarcity assessments. (A and C) The population affected at the global scale by water shortage and stress respectively under fixed, summed, and transient conditions. (B and D) The anomaly in estimated impact of the two driving forces 'changing socioeconomic conditions' and 'hydro-climatic variability' on changes in the population affected by water shortage and water stress respectively, expressed in percentage-points.

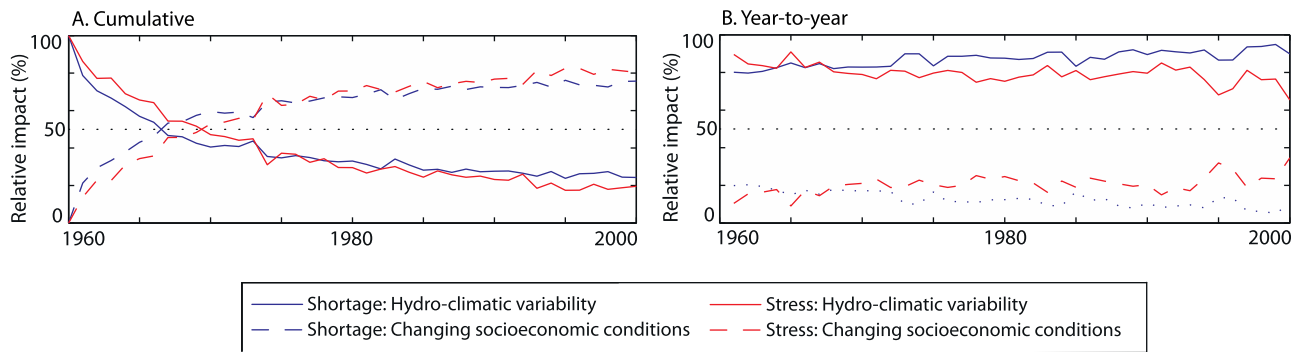


Fig. 5. Relative global scale contributions (%) of hydro-climatic variability and socioeconomic developments on overall cumulative (A) and year-to-year (B) changes in water shortage and water stress conditions over the period 1960–2000.

Moreover, we also found that, although socioeconomic changes are generally recognized as the most important driving forces of changes in water scarcity conditions, hydro-climatic variability can be held responsible for the largest share of the yearly change in water scarcity, with an average of 87.3% for shortage and 79.4% for stress at the global scale (Fig. 5B). Only after a period of six (shortage) to ten (stress) years of accumulating socioeconomic developments, changing socioeconomic conditions outweigh the impact of hydro-climatic variability (Fig. 5).

Fig. 6 shows the relative contributions of hydro-climatic variability and socioeconomic development on the cumulative changes in water scarcity conditions at the regional scale. By 2000, the largest differences between these two driving forces can be found in Caribbean (shortage) and Latin America (stress), with the smallest differences in Western Europe (shortage) and Northern Africa (stress). Supplementary Fig. S15 shows the tipping-point years per FPU for both water shortage and stress. Regional values on the relative contributions of the different driving factors on a year-to-year basis (i.e. not cumulative values) can be found in Supplementary Fig. S16 whilst the average relative contribution of hydro-climatic variability to the year-to-year changing in water scarcity conditions is summarized per FPU in Supplementary Fig. S17.

Fig. 7 shows the relative contributions of the different water consuming sectors on cumulative and year-to-year changes in water stress at the global scale. Globally, irrigation water use, domestic water use, and industrial water use are the sectors with the highest influence, both for the cumulative and year-to-year results. Considering the sectoral shares in water demand, we can make a clear distinction between regions within which changes in water stress values are mainly driven by industrial water demand, domestic water demand, or irrigation water demand, see Supplementary Figs. S18 and S19 for the results at the regional scale. In Supplementary Fig. S20, we show the socioeconomic sector with the largest relative impact per FPU, both when considering cumulative and year-to-year changes in water stress. Industrial water use exhibits the largest relative impact on water stress conditions in Northern America and Western Europe, while domestic water use has the largest relative contribution in Middle/South Africa, Australia/Pacific and China. In the other regions, irrigation water use is the largest driving socioeconomic driving force. Livestock water consumption only poses a relatively small impact on changes in water stress in Latin America, Australia/Pacific and China. The regional variation in our results could be related to, e.g. the type of a region's economy and its

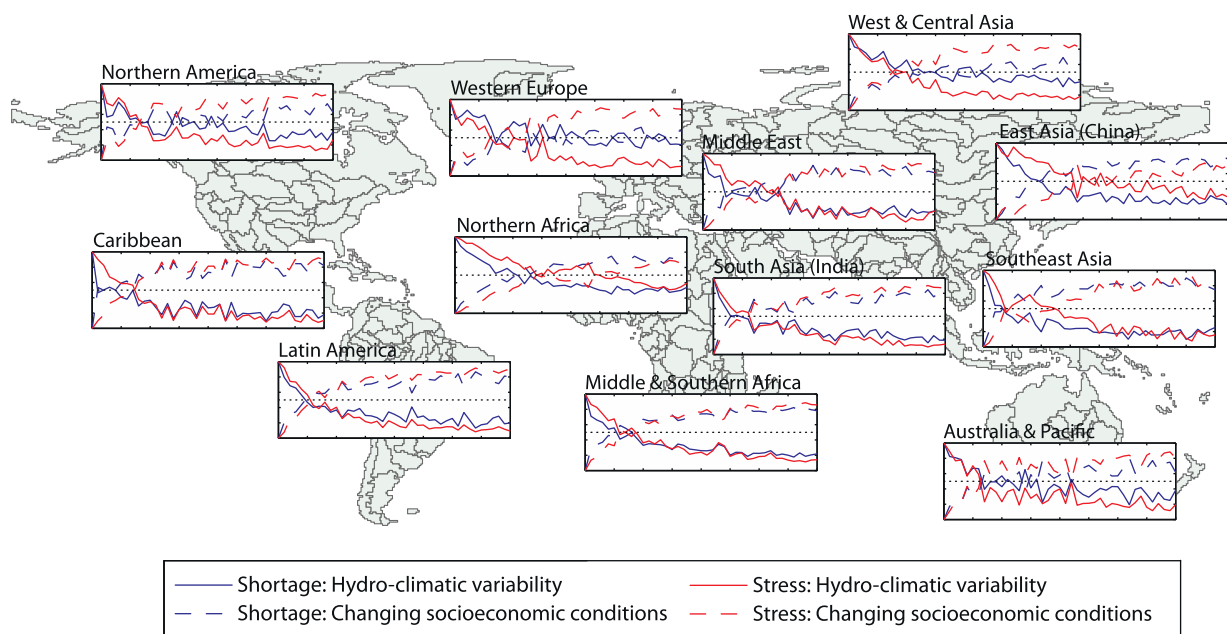


Fig. 6. Relative regional scale contributions (%) of hydro-climatic variability and socioeconomic developments to overall cumulative changes in water shortage and water stress over the period 1960–2000. The X and Y axis have the same scale as Fig. 5.

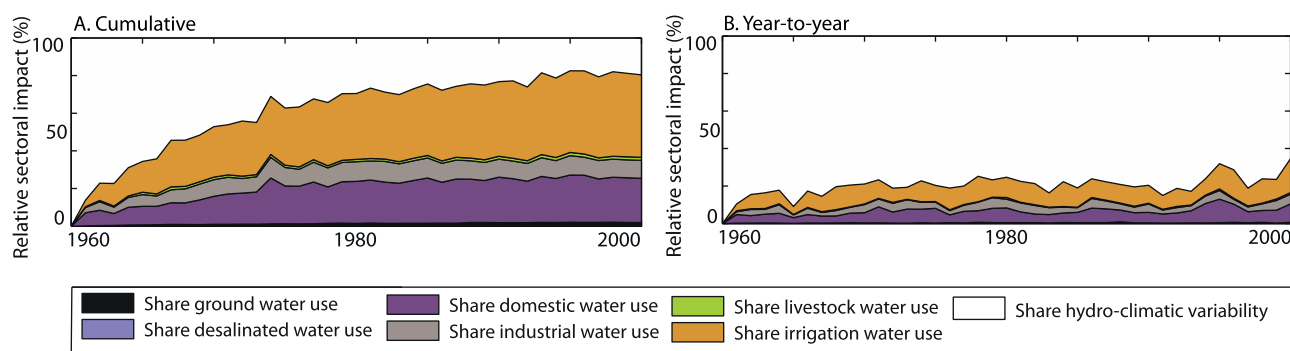


Fig. 7. Relative global scale contributions (%) of hydro-climatic variability and sectoral socioeconomic developments on overall cumulative (A) and year-to-year (B) changes in water stress over the period 1960–2000. Sectors that contribute to changes in water stress values are: ground water use, desalinated water use, domestic water use, industrial water use, livestock water use, and irrigation water use.

socioeconomic developments over time (Falkenmark et al., 2007; Flörke et al., 2013).

3.4. Cross-model validation

To assess the sensitivity of our results to the use of different water availability simulations, we re-ran the analyses with the individual water availability time-series of PCR-GLOBWB, STREAM, and WaterGAP, and evaluated their water availability and water scarcity estimates as well as estimates of the relative contribution to changes in water scarcity conditions. The results of the cross-model validation are discussed in detail in Supplementary Cross-model validation. In short, the validation exercise shows that yearly water availability estimates deviate up to 35.7% when comparing the different global hydrological models with the multi-model mean. This variation between models means that the results are sensitive to the choice of global hydrological model. However, whilst we found that the simulated water availability deviates up to 35.7%, the variation in the water scarcity assessments between models is much smaller, up to 26.3% and 16% for water shortage and stress respectively. This also holds also for the relative contribution of hydro-climatic variability and socioeconomic trends to changes in water scarcity conditions. In general, we found that the agreement between the different models agreement is relatively high when analyzing anomalies in water scarcity under partially fixed conditions, which supports the overall robustness of our findings.

4. Discussion

Within this study we executed a scenario analysis over the period 1960–2000 to assess the population affected by water scarcity and to define the drivers of change and associated mechanisms, globally and regionally. We visualized thereby for the first time the size of potential over- and underestimations in water scarcity assessments due to the use of long-term means instead of transient values. Moreover, we showed within this study that hydro-climatic variability accounts for more than 79% of the yearly change in water scarcity conditions, that it is the largest driver of change within the short-term (up to six-ten years), and that it remains to have a significance influence (>17.5%) on changing water scarcity conditions when considering longer time scales.

4.1. Policy implications

The findings presented in this study have key relevance for adaptation planning. It is known that adaptation is difficult and might be costly, ineffective and even wrong-targeted when

implemented using incomplete information (Hallegatte, 2009). For that reason, several climate change and adaptation studies have already emphasized the need for increased attention for research on variability and extremes, next to the ongoing work dealing with means and longer-term trends (Adger et al., 2005; Hall and Borgomeo, 2013; IPCC, 2012; Mason and Calow, 2012; Smit and Pilifosova, 2003).

Water scarcity is an important aspect in many high level policy targets, i.e. within the Sustainable Development Goals (UN, 2014) and the Hyogo Framework for Action (UNISDR, 2005). In developing the new Sustainable Development Goals, for example, one of the draft targets is “by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity”(UN, 2014, SDG 6.4). In order to achieve such targets, concrete performance indicators have to be defined to be able to measure its success, while at the same time one needs to have a correct estimate of how many are currently affected by water scarcity. Within this research we clearly show that in order to develop and correctly apply such water scarcity indicators, it is necessary to include hydro-climatic variability in water scarcity assessments. Hydro-climatic variability is an important driver of short to medium term changes in water scarcity conditions and omitting this variable can lead to unrealistic results not only regarding the estimated water scarcity conditions and the population affected by water scarcity events, but also in the relative contribution of socioeconomic changes and hydro-climatic variability on changing water scarcity conditions. The results provided by this study demonstrate, moreover, that, even if adaptation strategies to cope with future water scarcity conditions are designed and evaluated predominantly for their effects on longer time-scales, hydro-climatic variability remains a significant factor to take into account and to deal with. Climate variability, climate change and socioeconomic developments cannot exclusively be dealt with since it is the combination of all factors that shape future water scarcity conditions (IPCC, 2012; Klein, 2003). Thus, designing adaptation strategies solely based on changing means might not always be useful when dealing with the effects of current and future water scarcity conditions (Adger et al., 2005; Washington et al., 2006).

Water managers must consider climate variability as a key factor, both for designing strategies to cope with current water scarcity problems, as well as when selecting and designing robust adaptation strategies to cope with future conditions, ranging from hard technical adaptation strategies to softer management oriented adaptation options, such as risk transfer and financial compensation schemes (Aerts et al., 2014; Hall and Borgomeo, 2013; Kummur et al., 2014; Mason and Calow, 2012; Smit and

Pilifosova, 2003). Conway (2005) and Dono et al. (2013) illustrate this need, and show the potential of different types of adaptation strategies to deal with both climate variability and change in case studies of the Nile basin and Sardinia (Italy) respectively. Dessai and Hulme (2007) incorporate natural climate variability in their framework to identify robust adaptation decisions under climate change uncertainty in a case study in the East of England. On a global scale, Wada et al. (2014a) presents six strategies for counteracting the adverse impacts of socioeconomic developments, climate change and climate variability on water scarcity, evaluating both hard-path and soft-path measures, whilst Wilhite (2005) discusses the role of science and technology in drought and water management across multiple case studies (e.g. Australia, USA, and China) covering a wide range of adaptation strategies. In order to find a right balance between immediate short-term gains versus long-term investments, optimal adaptation to current and future water scarcity conditions often involves a portfolio of both hard and soft adaptation strategies (Adger et al., 2005; Aerts et al., 2014; Hallegatte, 2009; Klein, 2003). Engineering driven, 'hard path' strategies, such as increased reservoir capacity or a higher volume of desalination of sea water, have the ability to buffer short-term variability and to deal with long-term changes in future water scarcity conditions. In order to optimize the adaptive capacity of such strategies, i.e. make their design robust to a wide array of future circumstances, water managers should base their estimates on a range of future scenarios thereby covering the future impacts of inter-annual variability and taking into account possible worst-case conditions (Hall and Borgomeo, 2013; Hallegatte, 2009; Klein, 2003; Wilby and Dessai, 2010). The impact of climate variability on the operational forecast and management of reservoirs was discussed earlier by Georgakakos et al. (1998) for a case study in the Upper Des Moines River basin (USA). The same authors showed for a case study in Northern California (Georgakakos et al., 2012) that adaptive, risk based reservoir adaptation strategies, which have the ability to deal with increases in variability under climate change, perform more robustly under future conditions than the traditional rigid operation plans.

Considering the shorter time-scales, management driven, 'soft path' adaptation strategies might be preferred in the light of their flexible characteristics: such strategies are often reversible, no-regret, and therefore robust (Hallegatte, 2009; Hulme et al., 1999). Examples of soft adaptation strategies range from water transfers; adaptation of water demand; and supply management systems via economic policy instruments (e.g. pricing schemes, insurances, and water rights); the development of drought management plans and (participatory) institutional frameworks at the continental (e.g. the European Water Framework Directive (Heinz et al., 2007)) or country (e.g. the Spanish Permanent Drought Commission (Andreu et al., 2007)) scale. A wide range of case study examples discuss the potential of these types of adaptation strategies coping with variable water scarcity conditions, with applications at the global to local scales, see for example: Bozzola and Swanson (2014), Brandes and Kriwoken (2006), Erfani et al. (2015), Giansante et al. (2002), Iglesias et al. (2007), Kummu et al. (2014), Lundqvist and Falkenmark (2010), and Rosegrant and Gazmuri (1995). In the light of inter-annual variability, a specific type of soft adaptation is improved forecasting on seasonal or yearly scales and any related preparatory risk reduction actions, for example with the use of ENSO (El Niño Southern Oscillation) indices (Ward et al., 2014). Ample case study results show the potential effectiveness of such forecasting systems when coping with water scarcity conditions and fast developments take place regarding the institutionalization of these practices in water resource management, with examples ranging from the pre-stocking of foods and disaster relief goods in Africa (Coughlan de Perez and Mason, 2014; Dilley, 2000), ENSO-based crop insurances

in Malawi (Suarez et al., 2008), to the optimization of existing reservoir facilities in Australia (Sharma, 2000).

4.2. Limitations and recommendations for future research

This study provides a global scale assessment of the relative contribution of hydro-climatic variability and socioeconomic developments on water scarcity. Of course, given the global scale there are several limitations. Firstly, whilst the assessment was carried out at the FPU-scale, the results are mainly presented at the regional scale. These spatial scales may be too coarse to detect local water scarcity issues. However, this study intends to provide an overview of those regions where water scarcity issues exist, and to assess the over- and underestimations caused by omitting hydro-climatic variability or holding the socioeconomic conditions constant. For the assessment of local scale problems, other methodologies are required, including not only finer models, but more importantly stakeholder analysis and the collection of local data and knowledge. Secondly, we estimated water scarcity using naturalized flows, whilst in reality human consumption impacts on discharge levels and intensifies hydrological drought at local scales (Wada et al., 2013). Related to this point, we did not account for water imports and exports, which could illustrate the second order impacts of local water scarcity conditions towards other regions, e.g. due to increasing food prices (Dalin et al., 2012a,b; Hoekstra et al., 2012; Islam et al., 2007). Thirdly, the use of thresholds to estimate water shortage and stress brings several constraints. Besides the fact that different studies apply different indicators and threshold values to define water shortage and stress, the use of thresholds can cause sudden increases and decreases in the population affected by scarcity events, thereby disguising more nuanced changes in water scarcity over time. Applying continuous water scarcity conditions when studying anomalies in water scarcity assessments, rather than using thresholds, could help to address this issue. The downside of studying anomalies on continuous scales is that positive or negative anomalies with the same magnitude may not necessarily be equal in terms of their impacts on society.

It is evident that the (relative) contributions of socioeconomic changes and hydro-climatic variability on water scarcity conditions are highly dependent on the choice of its reference scenario, both in socioeconomic as in climatological sense. The global and regional results presented here underpin the relative importance of socioeconomic developments on changing water scarcity levels over 1960–2000, especially in fast developing regions, a notion supported by Wada et al. (2011a). Although these regions might not experience water scarcity yet, continuously changing socioeconomic conditions in the coming years could push them towards and over these water scarcity thresholds. Most developed regions experienced however a flattening in socioeconomic changes (growth in population, GDP, and/or irrigated areas) throughout 1960–2000. Lengthening the study period from 1960 to 2000 to e.g. 1900–2010 or even longer time-periods could strengthen the results presented in this paper. Such a longer time-series would also enable the analysis of climate trends and their relative contribution on changing scarcity conditions on top of the driving factors socioeconomic development and hydro-climatic variability studied in this paper.

Finally, the actual impact of water scarcity events depends not only on the number of people affected, but also on how sensitive this population is to water scarcity, how quickly and efficiently governments deal with the problems induced by water scarcity, and how many resources are available to cope with water scarcity (Arnell and Delaney, 2006; Falkenmark, 2013b; Gleick, 1998; Hoekstra et al., 2012; Kundzewicz et al., 2008; Wutich et al., 2014). A comprehensive sensitivity analyses focusing on the limitations

mentioned above could be an appropriate follow-up of this study to explore the sensitivity of the results presented. Future research should take into account a number of welfare indicators within the assessment of water scarcity conditions, thereby focusing on the 'adaptive capacity' of the affected population and the regulations in place to deal with water scarcity, but also looking at antecedent conditions such as previous water shortages.

5. Conclusions

In this paper we present a global scale water scarcity assessment that accounts for temporal changes in both socioeconomic conditions and inter-annual climate variability. Using a scenario analysis, we visualized for the first time the possible over- and underestimations that may have been made in previous water scarcity assessments due to the use of partially fixed conditions in their analyses. 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. Moreover, we showed that carrying out a water scarcity assessment with either fixed socioeconomic or fixed hydro-climatic conditions leads to unrealistic results regarding the estimated water scarcity conditions, the population affected by water scarcity events, and the contribution of socioeconomic changes and hydro-climatic variability on changing water scarcity conditions. Therefore, we devised a new way to analyze the relative contributions of these two driving mechanisms. In doing so, we found that hydro-climatic variability accounts for the largest share (>79%) of the yearly changes in global water scarcity conditions, whilst only after six (shortage) to ten years (stress), socioeconomic changes outweigh the impacts of hydro-climatic variability on global changes in water scarcity. Despite the accumulation of socioeconomic developments over time, our results show that the growth in the relative contribution of socioeconomic developments to changes in water scarcity levels stabilizes towards 2000, globally at 76.2% (shortage) and 82.5% (stress), and that the impact of hydro-climatic inter-annual variability remains significantly important.

This knowledge may be of importance for water managers optimizing the design of adaptation strategies coping with water scarcity as it is especially this time-period of six to ten years that is often applied by decision-makers as their horizon for planning and design. Moreover, the results of this study could be of use for development agencies, financing institutes and high-level policy makers as water scarcity is an important aspect on their agenda. Correct information on the current situation and on the relative contribution of driving forces shaping future conditions is essential for the prioritization and optimization of their adaptation, development and disaster risk reduction efforts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.gloenvcha.2015.02.011](https://doi.org/10.1016/j.gloenvcha.2015.02.011).

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