Towards a global water scarcity risk assessment framework: incorporation of probability distributions and hydro-climatic variability

T I E Veldkamp\textsuperscript{1}, Y Wada\textsuperscript{2,3,4}, J C J H Aerts\textsuperscript{1} and P J Ward\textsuperscript{1}

\textsuperscript{1} Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, The Netherlands
\textsuperscript{2} Center for Climate Systems Research, Columbia University, New York, USA
\textsuperscript{3} NASA Goddard Institute for Space Studies, New York, USA
\textsuperscript{4} Department of Physical Geography, Utrecht University, The Netherlands

E-mail: ted.veldkamp@vu.nl

Keywords: water scarcity, risk assessment, climate change, socioeconomic developments, global hydrological modeling, water resources, probabilistic methods

Supplementary material for this article is available online

Abstract
Changing hydro-climatic and socioeconomic conditions increasingly put pressure on fresh water resources and are expected to aggravate water scarcity conditions towards the future. Despite numerous calls for risk-based water scarcity assessments, a global-scale framework that includes UNISDR’s definition of risk does not yet exist. This study provides a first step towards such a risk-based assessment, applying a Gamma distribution to estimate water scarcity conditions at the global scale under historic and future conditions, using multiple climate change and population growth scenarios. Our study highlights that water scarcity risk, expressed in terms of expected annual exposed population, increases given all future scenarios, up to $>56.2\%$ of the global population in 2080.

Looking at the drivers of risk, we find that population growth outweigh the impacts of climate change at global and regional scales. Using a risk-based method to assess water scarcity, we show the results to be less sensitive than traditional water scarcity assessments to the use of fixed threshold to represent different levels of water scarcity. This becomes especially important when moving from global to local scales, whereby deviations increase up to 50% of estimated risk levels.

1. Introduction
Water scarcity, the inability of water resources to meet water demands (Young 2005, Hanemann 2006, Rijswijk 2006), is considered to be one of the most important global risks for society (Howell 2013). Changes in hydro-climatic conditions and socioeconomic developments have led in recent decades to an aggravation of water scarcity conditions at global and regional scales (Alcamo et al 1997, Vörösmarty et al 2000, Kummu et al 2010, van Beek et al 2011, Wada et al 2011, van Vliet et al 2013, Veldkamp et al 2015a, 2015b). Projected increases in human water demands due to changing lifestyles and a growing population, and projected changes in hydro-climatic conditions, are expected to increase both the probability of water scarcity events, as well as their societal impacts (Vörösmarty et al 2000, Stahl 2001, Lehner et al 2006, Alcamo et al 2007, Arnell et al 2011, 2013, Sperna Weiland et al 2012, Gosling and Arnell 2013, Hanasaki et al 2013, van Vliet et al 2013, Arnell and Lloyd-Hughes 2014, Haddeland et al 2014, Prudhomme et al 2014, Schewe et al 2014, Schloesser et al 2014, Wada et al 2014, Kiguchi et al 2015).

To deal with the uncertainty of climate change and future socioeconomic conditions, and to express their impacts on society, risk-based approach need to be integrated in water management (Kundzewicz et al 2008, Döll et al 2015, UNISDR 2015). An important first step therein that is already covered by many studies is the use of multiple global circulation models...
(GCMs) or global hydrological models (GHMs) in the assessment of water resources availability, water scarcity, or hydrological extremes, not seldom in combination with multiple scenarios or pathways covering a wide range of potential future climatic and socioeconomic conditions (e.g. Vörösmarty et al. 2000, Arnell 2004, Alcamo et al. 2007, Arnell et al. 2011, 2013, Döll and Schmied 2012, Crosbie et al. 2013, Davie et al. 2013, Gosling and Arnell 2013, Hanasaki et al. 2013, Dankers et al. 2014, Schewe et al. 2014, Schlosser et al. 2014, Wada et al. 2014a, 2014b, Shen et al. 2014, Kiguchi et al. 2015). Presenting the full range of impacts in combination with a (weighted) ensemble-mean is a good way to deal with the probability of occurrence of a future state and its impacts (Döll et al. 2015). However, it does not yet cover completely the ‘hazard’ in the UNISDR (2009) definition of risk in which the ‘hazard’ should be described quantitatively by ‘the likely frequency of occurrence of different intensities’ (UNISDR 2009), covering not only long-term mean states but also variability and extremes (IPCC 2012).

Risk assessment methods facilitate the inclusion of variability and provide insights in the severity, distribution, and impacts of both high and low probability events via the use of probabilities (Paté-Cornell 2012, Hall and Borgomeo 2013, Ward et al. 2014b) and may help improve the design and correct targeting of adaptation strategies (Smit and Pilifosova 2003, Adger et al. 2005, IPCC 2012, Mason and Calow 2012, Hall and Borgomeo 2013, Aerts et al. 2015, Döll et al. 2015). The probabilistic treatment of variability and extremes is well-known for its use in the evaluation of hydrological states (McKee et al. 1993, Stedinger et al. 1993, Tallaksen 2000, Stahl 2001, Döll et al. 2003, Tallaksen et al. 2004, Shukla and Wood 2008, Vincente Serrano et al. 2010) and risk assessment methods—covering hazard, exposure, and vulnerability (UNISDR 2009, IPCC 2012)—have been adopted previously to express risk in other hydro-meteorological perils or in operational reservoir management (Burn et al. 1991, Ko et al. 1992, Nardini et al. 1992, Ward et al. 2013). So far, only few studies have, however, actually applied risk-based principles in the assessment and evaluation of water scarcity at a regional scale (Rogers and Fiering 1986, Hall and Borgomeo 2013, Borgomeo et al. 2014, Turner et al. 2016) and, to the best of our knowledge, a global scale water scarcity risk assessment is missing yet.

To address this issue, we establish a first step towards a framework for global water scarcity risk assessments that covers the first two perils of the UNISDR (2009) risk definition (hazard and exposure) and uses probabilistic methods to deal with variability and extremes. In this contribution we present the first insights of our study and discuss the steps that need to be taken to complete the proposed framework for the assessment of water scarcity risks.

2. Methods

In short, we carried out this assessment through the following steps (figure 1): (1) calculated yearly water availability (0.5° × 0.5°) over the period 1971–2099 using daily run-off from the GHM PCR-GLOBWB, forced with different climate change projections (representative concentration pathways or RCPs) from the ISI-MIP project (www.isi-mip.org, Warszawski et al. 2014); (2) fitted a Gamma distribution through the time-series of yearly water availability covering historic, 2030, 2050, and 2080 conditions and estimated water availability for 999 return periods, varying from 1 up to 1000 years; (3) calculated water scarcity conditions by assembling the water availability results with scenario estimates of population density (shared socioeconomic pathways or SSPs); (4) assessed risk (covering hazard and exposure) in terms of the...
expected annual exposed population (EA-EP) and estimated the fraction of risk being attributable to the driving forces climate change, socioeconomic developments, or a combination of both; and (5) compared the use of such a risk-based method in water scarcity assessments to the use of long-term mean values to assess water scarcity. The following paragraphs describe our methods in detail.

2.1. Calculating water availability

In this study we used daily run-off (0.5° x 0.5°) from the GHM PCR-GLOBWB to calculate yearly water availability (van Beek et al. 2011, Wada et al. 2014b). PCR-GLOBWB was forced using meteorological data (0.5° x 0.5°), from five global climate models (GCMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) (Hempel et al. 2013), each of them representing three representative concentration pathways (RCPs: van Vuuren et al. 2011, Taylor et al. 2012): RCP2.6, RCP6.0 and RCP8.5. The meteorological data was bias-corrected towards the WATCH observation based dataset (Weedon et al. 2011) using an established method of Hempel et al. (2013). The resulting daily run-off values per RCP were aggregated into yearly totals per water province. Water provinces are a composite of river basins and administrative regions (Stratsma et al. 2014). Within this study, we distinguished 1514 water provinces with a mean and median size of 83 663 km² and 48 663 km² respectively (supplementary figure A1). The use of hydrological years instead of calendar years is needed since the statistical analysis (section 2.2) requires the time-series to be independent (Leadbetter et al. 1983, Katz et al. 2002). We used long-term mean maximum water availability as a proxy for the distinction between two types of hydrological years: October–September; July–June (Ward et al. 2014a, Veldkamp et al. 2015a).

2.2. Probabilistic water availability and water scarcity assessments

Subsequently, we fitted per water province and for each GCM-RCP combination a Gamma distribution through four 30 year time slices of annual water availability: historic (1975–2004); 2030 (2015–2044); 2050 (2035–2064); and 2080 (2065–2094). A Gamma distribution was used because its distribution is zero-bounded and therefore well able to reflect water availability. Moreover its scale and shape parameters enable the representation of a wide variety of distribution shapes (Wilks 1990, 1995, Thom 1958, Husak et al. 2007). We tested the accuracy of the estimated Gamma parameters in approximating its original distribution with the Kolmogorov–Smirnov or Lilliefors test (Crutcher 1975, Wilks 1995, Husak et al. 2007) using P-values of ≥0.001 (supplementary figure A2). The ‘accurate’ Gamma parameters were used to estimate the annual water availability per water province for 999 return periods, from 1 up to 1000 years, thereby continuously accounting for the probability of zero water availability (Wilks 1990, Stedinger et al. 1993).

Water scarcity conditions were expressed with the water crowding index (WCI), a simple but often used indicator that estimates the annual water availability per capita (Falkenmark 1986, 2013, Rijsberman 2006), see equation (1):

\[
\text{WCI}_{i, y, P, r, c, p, a} = \frac{\text{WA}_{i, y, P, r, c, p}}{P_{i, y, a}} \quad \text{(moderate water scarcity event if WCI}_{i, y, t} \leq 1700),
\]

where \( \text{WCI}_{i, y, P, r, c, p, a} \) is the water availability per capita in water province \( i \), time slice \( t \), return period \( r \), climate change projection \( c, p \), and socio-economic scenario \( s, p \); \( \text{WA}_{i, y, P, r, c, p} \) is the total water availability in water province \( i \), time slice \( t \), return period \( r \), and climate change projection \( c, p \); and \( P_{i, y, a} \) is the total population in water province \( i \), time slice \( t \), and population growth scenarios \( s, p \). We used \( \leq 1700 \) m³/capita per year as the threshold for water scarcity (Kummu et al. 2010). Moreover, we distinguished between moderate (\( \leq 1700 \) m³/capita per year), severe (\( \leq 1000 \) m³/capita per year), and absolute (\( \leq 500 \) m³/capita per year) water scarcity conditions (Kummu et al. 2010).

The population estimates used in this study to calculate the WCI were derived from the shared socioeconomic pathways (SSPs: van Vuuren et al. 2007, 2011, O’Neill et al. 2012, 2015). Although theoretically each SSP could be combined with each RCP, some combinations of SSP and RCP are not expected to develop in the real world (Arnell and Lloyd-Hughes 2014). Therefore, we followed Winsemius et al. (2015) who set-up three combinations of RCPs and SSPs (table 1): sustainability (RCP2.6-SSP1), fragmented world (RCP6.0-SSP3), and fossil-fuel based (FFB) development (RCP8.5-SSP5). We refer to Winsemius et al. (2015) for a detailed explanation on the development of these storylines.

2.3. Estimating and evaluating risk

The resulting WCI values were plotted on exceedance probability curves. Implementing the thresholds of 500, 1000, and 1700 m³/capita per year resulted for each GCM-storyline combination and for each time-slice in an exceedance-probability impact curve per water province. In this study, we expressed impact as the population exposed to water scarcity events. One should keep in mind, however, that the actual impact of water scarcity is not only influenced by exposure, but also by the vulnerability to water scarcity (Gleick 1998, Arnell and Delaney 2006, Kundzewicz et al. 2008, Hoekstra et al. 2012, Falkenmark 2013, Wutich et al. 2014). Finally, risk was estimated as the area under the exceedance-probability impact curve (Meyer et al. 2009) and is expressed here as the EA-EP. To evaluate the contribution of the driving forces
climate change and population growth to the changes in risk levels towards 2080 separately, we repeated the complete risk analysis (section 2.1–2.3) with two more runs: (1) a run with transient climatic conditions and fixed (historic) population density conditions; and (2) a run with fixed (historic) climatic conditions and transient population growth conditions.

3. Results

Global scale water scarcity risk (EA-EP) increases towards 2080 under all storylines (figure 2). While risk more than doubles under the storylines sustainability and FFB development, it increases with more than three-fold under the storyline fragmented world. Also when risk is expressed in relative terms (EA-EP as percentage of the total population), global risk levels increase towards 2080, from 38.0% under historic conditions, up to 67.8% (fragmented world), 56.2% (sustainability), and 59.1% (FFB development).

GCM uncertainty is relatively small at the globally aggregated scale, with deviations from the ensemble-mean up to 3.2% in 2080. Uncertainty is larger under severe ("1000 m³/capita per year) and absolute (≤500 m³/capita per year) water scarcity, with deviations in 2080 up to 5.8% and 16.1% respectively (supplementary table B1). Making a distinction between moderate, severe, and absolute water scarcity, we find that the increases in global risk are dominated by increases in absolute water scarcity risk, and least driven by changes in moderate water scarcity risk (supplementary figure A3 and table B2). When comparing the global scale risk estimates using risk-based

### Table 1. Storylines with their associated narratives for the representative concentration pathways (RCPs) and the shared socio-economic pathways (SSPs), taken from: van Vuuren et al (2011), O’Neill et al (2015), Winsemius et al (2015).

| Storyline             | RCPs       | SSPs                  |
|-----------------------|------------|-----------------------|
| Sustainability        | RCP2.6     | SSP1                  |
|                       | Peak in radiative forcing at ~3 W m⁻² (~490 ppm CO₂ eq) before 2100 and then decline (the selected pathway declines to 2.6 W m⁻² by 2100). | Rapid technology for fossil fuelsHigh energy demandHigh economic growthLow population |
| Fragmented world      | RCP6.0     | SSP2                  |
|                       | Stabilization without overshoot pathway to 6 W m⁻² (~850 ppm CO₂ eq) at stabilization after 2100 | Slow technologyDevelopment (dev-ing)Reduced tradeVery slow economic growthVery high population |
| Fossil-fuel Based     | RCP8.5     | SSP5                  |
| development           | Rising radiative forcing pathway leading to 8.5 W m⁻² (~1370 ppm CO₂ eq) by 2100 | Rapid technologyHigh energy demandHigh economic growthLow population |

Figure 2. Development of the absolute (a) and relative (b) water scarcity risk levels. The colored squares show the global risk levels (EA-EP) under the different storylines for the time-slices: historic, 2030, 2050, and 2080. GCM uncertainty is visualized as the colored shaded areas around the scatters. The colored asterisks show the global mean exposed population (M-EP) under the different storylines using a 30 year mean water availability estimate as input for each time-slice for the risk assessment.
methods (EA-EP) with the results of conventional water scarcity methods using long-term means (M-EP), we find only minor deviations that fall within the GCM modeling uncertainty for the storylines sustainability and fragmented world. Whilst risk estimates using the M-EP approach are lower than those using the EA-EP approach for moderate water scarcity events, we find an opposite signal when looking at absolute scarcity events. For severe scarcity events we did not find a uniform signal across the different storylines (supplementary table B3).

Large geographical differences in risk exist across the different world regions (figure 3) and water provinces (supplementary figure A4). Using the $\leq 1700$ m$^3$/capita per year as indicator for water scarcity, the highest relative risk estimates in 2080 were found in Northern Africa (85.2%—fragmented world), whilst the lowest values were found in the Middle East (18.8%—sustainability). By 2080, the highest increases in relative risk levels were found in the Caribbean (up to 50 percentage-points increase—FFB development), compared to stable relative risk levels in the Middle-East (up to 9.3 percentage-points increase—fragmented world), see also supplementary figure A5 for the results per water province. Regionally, all GCM models support the found GCM ensemble-mean increase/decrease in risk levels per storyline. Whilst modeling spread is relatively high in Australia and the Pacific, the Caribbean, Northern Africa, and Northern America (figure 3), high modeling agreement (increase/decrease) was found at the level of water provinces (supplementary figure A5). Comparison of the M-EP with the EA-EP outcomes at global, regional and local scales, shows that deviations between M-EP and EA-EP increase up to 50% of EA-EP at local scales (figures 2 and 3, supplementary figure A6).

Looking at moderate, severe, and absolute water scarcity conditions and their associated risk levels separately (figure 4), shows that large regional differences exist under historic and future conditions. Moderate and severe water scarcity risk levels dominate in Australia and Pacific, Northern America, West and Central Asia, Western Europe, and India (>50% of the found total EA-EP levels). At the same time, Northern Africa experiences the highest relative risk levels in 2080 under storyline fragmented world, not only when looking at the composite of all water scarcity
Figure 4. Global and regional scale EA-EP levels in 2080 under storyline fragmented world whilst using the GCM ensemble mean data. EA-EP levels are expressed as % of the total population and share of the different water scarcity severity classes (moderate, severe, absolute) in total EA-EP are visualized by means of the different colors applied.

Figure 5. Global scale attribution of risk, expressed in terms of percentage-point change in expected annual exposed population (EA-EP, relative to the global population). Gray bars show risk under historic conditions whereas the colored bars show per storyline (a)–(c) the attribution of the estimated changes in risk to climate change (green), population growth (red), and a combination of factors (purple) for 2030, 2050 and 2080. Sub-figures (II) show for each storyline (a)–(c) the absolute attribution to change, whereas sub-figures (III) present the attribution in relative terms as a share of the total change in EA-EP.
severity classes, but also when taking into account only
the absolute water scarcity. Increases in risk under the
storyline fragmented world are dominated by increases
in absolute and severe water scarcity risk in almost
all world regions, whilst the levels of EA-EP to moder-
ate water scarcity remain relatively stable or decrease
over time (figure 4 and supplementary figure A7).

Population growth is the largest contributor to
increases in water scarcity risk at the global and region-
al scale, irrespective of the storyline and time-slice studied (figure 5). The foreseen increases in popu-
lation density increase risk in all world regions and
under all storylines, whilst the climate change attribu-
tion to changing risk levels is more diverse (supple-
mentary figures A8–A10). Negative contributions of
projected climate change (supplementary figure A11, presented by means of changes in mean yearly water
availability and its inter-annual variability) to the
change in water scarcity risk (i.e. resulting in lower risk) are, for example, found for the Middle East,
Northern Africa, West and Central Asia, and the Car-
ibbean. The combined factor ‘climate change + po-

gulation growth’ is a factor that accounts for the
differences in risk estimates when looking at projected
climatic change or population growth individually,
compared to the estimated actual change (full change)
in EA-EP (figure 5 and supplementary figures A8–
A10). It should be interpreted as a factor that char-
acterizes the interaction between the two individual
driving forces.

The spatial visualization of the largest drivers of
risk towards 2080 (figure 6) shows once more that
water scarcity is not solely a climate change problem,
but an issue that constitutes from the developments in
both the supply of and demand for fresh water resour-
ces. When looking at water provinces in Europe,
Northern Africa, Northern America, Latin America,
the Middle East, and India we find clear differences
between the three storylines both with respect the
actual changes in risk and regarding the largest con-
tributor of changing risk levels. Due to the relative low
population growth and climate change projections
under storyline sustainability, water scarcity risk levels
do not change in a significant amount of regions in
Europe, West and Central Asia, and China. Remark-
able is the relatively large share of water provinces for
which the change in risk is dominated by population
growth as well as its distinct spatial distribution, cover-
ning 21.6% of the total land area, and 30.7% of the
population (under historic conditions) under the frag-
mented world storyline. Under the FFB development
storyline, population growth is the largest driver of
changing risk levels in water provinces covering 13.1% of
the total land area and 27.3% of the population (at
historic conditions), whilst climate change induces
changes in risk mostly in 6.3% and 14.6% of the total
land area, and 14.4% and 21.0% of the population (at
historic conditions) under the storylines fragmented
world and FFB development respectively. The
combined factor climate change and population
growth is a significant factor of influence in the FFB
Development storyline, covering 12.9% of the total
global land area.

4. Discussion and conclusions

In this study we presented a global scale water scarcity
assessment based on the principles of a risk analysis.
Given the wide variety of GHMs used, the different
climate change projections and socioeconomic sce-
narios applied, and the use of different metrics to
assess water scarcity, we found that our global water
scarcity (risk) estimates are consistent with global
results presented in earlier studies (e.g. Revenga
et al 2000, Arnell 2004, Alcamo et al 2007, Hayashi
et al 2010, Arnell et al 2011, Gosling and Arnell
2013, Hanasaki et al 2013, Arnell and Lloyd-Hughes
2014, Schewe et al 2014, Schlosser et al 2014, Shen et
al 2014, Wada et al 2014a, Kiguchi et al 2015), see supple-
mentary table B4. The use of a Gamma distribution to
represent the yearly water availability enabled us to
cover with numerous return periods the inter-annual
variability in water availability as well as the low-
probability events that are normally not included
(Paté-Cornell 2012, Hall and Borgomeo 2013). Com-
pared to the conventional water scarcity assessments,
the estimates presented in this study are therefore less
sensitive to the use of strict water scarcity thresholds,
which can cause jumps in the estimated water stressed
population or regions (Gosling and Arnell 2013,
Veldkamp et al 2015b). This becomes especially
important when moving from global, to regional, to
local water scarcity risk estimates, whereby deviations
between M-EP and EA-EP may increase up to 50%.

In line with earlier studies (supplementary table
B4), we found that global and regional water scarcity
risk increases towards 2080. Moreover, the results
show that population growth outweigh the impacts of
climate change at the global and regional scale, under
all storylines. Also at local scales, we found population
growth to be the largest driver of change in a majority
of water provinces, for example under storyline frag-
mented world. For the FFB development storyline,
however, we found that the changes in risk levels are
predominantly driven by climate change in a majority
of water provinces. The results show that disaggrega-
tion to different spatial scales is important: the use of
a single scale might obscure water scarcity problems at
other scales and may hamper the evaluation of poten-
tial underlying causes (Hering et al 2015, Vörösmarty
et al 2015).

By using local run-off as a parameter to estimate
water availability, it is important to note that this study
does not account for upstream–downstream relations.
The inclusion of these relations across water provinces
would require a separate study modeling multivariate
extreme values using copulas or other statistical
Such a study should also take into account the impacts of upstream water withdrawals of all sectors under the different socioeconomic and climate change projections applied (e.g. Wada et al 2016), data that was not available yet when performing our analysis. By using naturalized flows, we have not taken into account the water resources available in man-made managed reservoirs, in ground water storages, or from

**Figure 6.** Regional scale variation in the attribution to changes in risk (EA-EP) in 2080 compared to the historic conditions under the storylines: (a) sustainability, (b) fragmented world, and (c) fossil-fuel based development. Figures (a)–(c) show per water province the largest contributor to the expected change in risk: climate change (green), population growth (red), or a combination of both (purple).
desalination plants, nor did we include any infrastructure for the transfer of water. Water availability values presented within this study should be therefore interpreted as conservative (i.e. lower-end estimates), leading to higher-end risk estimates. Despite the fact that water quality and water quantity conditions are highly interdependent, we did not account for water quality conditions in this study. Insufficient water quality conditions are expected to become more important towards the future (e.g. Jiang et al. 2014) and could severely limit the availability of fresh water resources for use. Extending the water scarcity risk assessment framework with a water quality module could therefore enhance the water scarcity risk estimates as presented in this study.

This study used only one GHM to estimate water scarcity risk. Although previous research has shown that the PCR-GLOBWB model estimates fit well within the ensemble of frequently used GHMs (Schewe et al. 2014, Wada et al. 2016) it is recommended to use an ensemble of models as the GHM spread exerts a significant influence on the range of outcomes (Schewe et al. 2014, Döll et al. 2015). The difficulty of GHMs to model water availability in desert areas (van Huigenhoort et al. 2012, Wada et al. 2013) is reflected in this study by the absence of good Gamma-fit estimates and the inability to draw probability-density curves for these water provinces. Although these areas exhibit only a minor share of the global total population (supplementary figure A2), one should take into account that the inability to model these regions in an appropriate manner leads to underestimations in risk levels, especially in Northern Africa.

PCR-GLOBWB was forced in this study with meteorological forcing data from five GCMs, being bias-corrected following Hempel et al. (2013). Hempel et al. (2013) showed that the bias-correction method applied is able to improve the matching of both the variability within, as well as the long-term means of, different simulated meteorological values with observations (WATCH Forcing Data, Weedon et al. 2011). Even in the tails of the distribution, Hempel et al. (2013) found a relatively good agreement with the observation data-set. Hempel et al. (2013) did not bias-correct, however, the representation of persistence, which might influence possibly the representation of inter-annual variability (Rocheta et al. 2014). To account for this, a new nested-bias-correction method could be adopted in future studies (Rocheta et al. 2014, Mehrotra and Sharma 2015). To evaluate the potential bias between the GCM derived simulations used in this study and observational data, we compared the water scarcity risk estimates using the GCM data with risk estimates using the WATCH Forcing Data Era Interim (WFDEI; Weedon et al. 2014), see supplementary figure A12. We found that the GCM derived simulations overestimate risk slightly at global scale (3.2 percentage-point) and in nine world regions (from 0.4 up to 6.6 percentage-point). For Middle East (−0.7 percentage-point), Southeast Asia (−0.1 percentage-point), and Australia and the Pacific (−0.1 percentage-point), we found a small underestimation in risk levels using the GCM derived simulations compared to the WFDEI.

Risk is expressed in this study by means of the (EA-EP) to water scarcity. A potentially exposed population, however, does not per se imply (economic) impact. To come to a full risk assessment framework more work needs to be done to make the transfer from risk estimates in terms of exposed population towards estimates covering ‘economic’ impacts. A first step therein should be to include vulnerability, including: the sensitivity of a population to water scarcity, the available infrastructure and (financial) resources to cope with water scarcity, the portfolio of economic activities dependent on the available water resources, the dependency of an economy on local or external water resources, and capability of the responsible government to deal with water scarcity in an quick and efficient manner (Gleick 1998, Arnell and Delaney 2006, Kundzewicz et al. 2008, Hoekstra et al. 2012, Falkenmark 2013, Wutich et al. 2014, Lasage et al. 2015a, 2015b). Making the translation from exposure to economic impacts is an emerging research field using, among others, hydro-economic models and econometric optimization routines (Brouwer and Holkes 2008, Harou et al. 2009). So far, their application in risk-based assessments with a global reach has been, however, limited.

Improving the presented water scarcity risk assessment framework with the above mentioned considerations will offer water managers a promising perspective to achieve higher water security under current and future circumstances in a well-informed and adaptive manner. Risk-based methods are able to cover multiple aspects: the hazard size, reflecting the likelihood, uncertainty, and inter-annual variability of water scarcity events; as well as the impact of water scarcity events, covering exposure and vulnerability. Adopting a scenario-based approach within the assessment of water scarcity risks, moreover, provides insights in the impacts of inter-action among the different drivers of risk. A better understanding of the underlying driving forces of water scarcity risks can help decision makers to assign focus areas for different types of adaptation strategies (e.g. soft versus hard) and to develop portfolios of (cost-) efficient but low-to no-regret solutions to stabilize or reduce water scarcity risk at different spatial scales.

Acknowledgments

TIEV, JCJHA, and PJW designed research; TIEV and YW prepared datasets; TIEV analyzed data; and TIEV, YW, JCJHA, and PJW wrote the paper.
The research leading to this article is partly funded by the EU 7th Framework Programme through the projects ENHANCE (grant agreement no. 308438) and Earth2Observe (grant agreement no. 603608). J Aerts received funding from the Netherlands Organization for Scientific Research (NWO) VICI (grant no. 453-14-006). Y Wada is supported by Japan Society for the Promotion of Science (JSPS) Oversea Research Fellowship (grant no. JSPS-2014-878). P Ward received funding from the Netherlands Organization for Scientific Research (NWO) in the form of a VENI grant (grant no. 863-11-011). None of the authors of this article have a competing financial interest.

References

Adger N W, Arnell N W and Tompkins E L 2005 Successful adaptation to climate change across scales Glob. Environ. Change 15 77–86

Aerts J C J H, Botzen W J W and Werners S 2015 Portfolios of adaptation investments in water management Mitigation Adaptation Strategy Glob. Change 20 1127–65

Acamo J, Doll P, Kaspar F and Siebert S 1997 Global Change and Global Scenarios of Water Use and Availability: An Application of Water GAP1.0 Center of Environmental Systems Research, University of Kassel, Germany

Acamo J, Flörke M and Märker M 2007 Future long-term changes in global water resources driven by socio-economic and climatic changes Hydrol. Sci. J. 52 247–75

Arnell N W 2004 Climate change and global water resources: SRES emissions and socio-economic scenarios Glob. Environ. Change 14 31–52

Arnell N W and Delaney E K 2006 Adapting to climate change: public water supply in England and Wales Clim. Change 78 227–55

Arnell N W and Lloyd-Hughes B 2014 The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios Clim. Change 122 127–40

Arnell N W, van Vuuren D P andisaac M 2011 The implications of climate policy for the impacts of climate change on global water resources Glob. Environ. Change 21 592–603

Arnell N W et al 2013 A global assessment of the effects of climate policy on the impacts of climate change Nat. Clim. Change 3 512–9

Borgomeo E, Hall J W, Fung F, Watts G, Colguhoun K and Lambert C 2014 Risk-based water resources planning: incorporating probabilistic nonstationarity climate uncertainties Water Resour. Res. 50 6850–73

Brouwer R and Hofkes M 2008 Integrated hydro-economic modelling: approaches, key issues, and future research directions Ecol. Econ. 66 16–22

Burn D H, Venema H D and Simonovic S P 1991 Risk-based performance criteria for real-time reservoir operation Can. J. Civil Eng. 18 36–42

Chung C and Salas J 2000 Drought Occurrence probabilities and risks of dependent hydrologic processes J. Hydrog. Eng. 5 259–68

Crosoic R S, Pickett T, Mpeladaoka F S, Hodgson G, Charles S P and Barron O V 2013 An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs Clim. Change 117 41–53

Crutcher H L 1975 A note on the possible misuse of the Kolmogorov–Smirnov test J. Appl. Meteorol. 14 1600–3

Dankers R et al 2014 A first look at changes in flood hazard in the ISI-MIP ensemble Proc. Natl Acad. Sci. USA 111 3257–61

Davies J C S et al 2013 Comparing projections of future changes in runoff from hydrological and biome models in ISI-MIP Earth Syst. Dyn. 4 359–74

Doll P, Jimenez–Cisneros B, Oki T, Arnell N W, Benito G, Cooley J G, Jian T, Kuzdzejicz Z W, Mwakalalis S and Nishijima A 2015 Integrating risks of climate change into water management Hydrol. Sci. J. 60 4–13

Doll P, Kaspar F and Lehner B 2003 A global hydrological model for deriving water availability indicators: model tuning and validation J. Hydrol. 270 105–34

Doll P and Schmied H M 2012 How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis Environ. Res. Lett. 7 104037

Falkenmark M 1986 Fresh water—time for a modified approach Ambio 15 192–200

Falkenmark M 2013 Growing water scarcity in agriculture: future challenge to global water security Phil. Trans. R. Soc. A 371 20120410

Favre A–C, El Adlouni S, Perreault L, Thie’ monge N and Bobe’ e B 2004 Multivariate hydrological frequency analysis using copulas Water Resour. Res. 40 W01101

Gleck P H 1998 Water in crisis: paths to sustainable water use Ecological Appl. 8 571–9

Gosling S N and Arnell N W 2013 A global assessment of the impact of climate change on water scarcity Clim. Change 115 1417–1431

Haddeland I et al 2014 Global water resources affected by human interventions and climate change Proc. Natl Acad. Sci. USA 111 3251–6

Hall J W and Borgomeo E 2013 Risk-based principles for defining and managing water security risk-based principles for defining and managing water security Phil. Trans. R. Soc. A 371 20120407

Hanasaki N et al 2013 A global water scarcity assessment under shared socio-economic pathways: 2. Water availability and scarcity Hydrology, Earth Syst. Sci. 17 2393–413

Hannemann M W 2006 The economic conception of water 2006 Water Crisis: Myth or Reality ed P Rodgers et al (Leiden, The Netherlands: Taylor and Francis) p 332

Harou J J, Pulido–Velazquez M F, Rosenberg D E, Medellin–Azua J, Lund J R and Howitt R F 2009 Hydro-economic models: concepts, design, applications, and future prospects J. Hydrol. 375 627–743

Hayashi A, Akimoto K, Sanó F, Mori S and Tomoda T 2010 Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target Clim. Change 98 87–112

Hempel S, Frieler K, Warszawski L, Schewe J and Piontek F 2013 A trend–preserving bias correction—the ISI-MIP approach Earth Syst. Dyn. 4 219–36

Hering J, Sedlak D L, Tortajada C, Biswas A K, Nisagaba C and Breu T 2015 Local perspectives on water Science 349 479–80

Hoehne N, Mekonnen M M, Chapagain A K, Mathews R E and Richter B D 2012 Global monthly water scarcity: blue water footprints versus blue water availability PloS One 7 e26688

Howell L 2013 Global Risks 2013 World Economic Forum Geneva, Switzerland

Husak G J, Michaelen J and Funk C 2007 Use of the gamma distribution to represent monthly rainfall in Africa for drought monitoring applications Int. J. Climatol. 27 935–44

IPCC 2012 Managing the risks of extreme events and disasters to advance climate change adaptation A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change ed C B Field et al (Cambridge: Cambridge University Press) p 582

Jiang J, Sharma A, Sivakumar B and Wang P 2014 A global assessment of climate-water quality relationships in large rivers: an elasticity perspective Sci. Total Environ. 468–469 877–91
Katz R W, Parlane M B and Naveau P 2002 Statistics of extremes in hydrology Adv. Water Resour. 25 1287–104
Kiguchi M, Shen Y, Kanai S and Oki T 2015 Reevaluation of future water stress due to socio-economic and climate factors under a warming climate Hydrolog. Sci. J. 60 14–29
Ko S-K, Fontane D G and Labadie J W 1992 Multiobjective optimization of reservoir system operation Water Res. Bull. 28 111–127
Kummu M, Ward P J, de Moel H and Varis O 2010 Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia Environ. Res. Lett. 5 034006
Kundzewicz Z W, Mata I J, Arnell N W, Doll P, Jimenez B, Miller K A, Oki T, Sen Z and Shiklomanov I A 2008 The implications of projected climate change for freshwater resources and their management Hydrol. Sci. J. 53 3–10
Lasage R, Aerts J C J H, Verburg P H Hand Sileshi A S 2015a The role of small scale sand dams in securing water supply under climate change in Ethiopia Mitigation Adaptation Strategy. Glob. Change 20 317–39
Lasage R, Muis S, Sardella C S E, van Drunen M A, Verburg P H and Aerts J C J 2015b Vulnerability to climate change and community based adaptation in the Peruvian Andes, a stepwise approach Sustainability 7 1742–73
Leadbetter R M, Lindgren G and Rootzten H 1983 Extremes and Related Properties of Random Sequences and Processes (New York: Springer) p 336
Lehner B, Doll P, Alcamo J, Henrichs T and Kaspar F 2006 Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis Clim. Change 75 273–99
Mason N and Calow R 2012 Water Security: From Abstract Concept to Meaningful Metrics: An Initial Overview of Options Overseas Development Institute, London, UK
McKee T B, Doesken N J and Kleist J 1993 The relationship of drought frequency and duration to time scales Proc. 8th Conf. on Applied Climatology vol 17 pp 179–83
Mehrotra R and Sharma S 2015 Correcting for systematic biases in multiple raw GCM variables across a range of timescales J. Hydrol. 520 214–23
Meyer V, Haase D and Scheuer S 2009 Flood risk assessment in European river basins—concept, methods, and challenges exemplified at the Mulde River Integ. Environ. Assess. Manage. 5 17–26
Nardini A, Piccardi C and Sincinnesa R 1992 On the integration of risk-aversion and average performance optimization in reservoir control Water Resour. Res. 28 867–89
O’Neill B C et al 2012 Meeting report of the workshop on the nature and use of new socioeconomic pathways for climate change research Workshop Report (Boulder, CO: 2–4 November 2011) (Boulder: National Center for Atmospheric Research) (http://ispc.ucar.edu/socioeconomic-pathways)
O’Neill B C et al 2015 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century Glob. Environ. Change (doi:10.1016/j.gloenvcha.2015.01.004)
Paté–Cornell E 2012 On ‘Black Swans’ and ‘Perfect Storms’: risk analysis and management when statistics are not enough Risk Anal. 32 1823–33
Prudhomme C et al 2014 Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment Proc. Natl. Acad. Sci. USA 111 3262–72
Revega C, Brunner J, Henninger N, Kassem K and Payne R K 2000 Pilot Analysis of FreshWater Ecosystems: Freshwater Systems (Washington, DC: World Resources Institute)
Rübsamen F 2006 Water scarcity: fact or fiction? Agric. Water Manage. 80 5–22
Rocheta E, Sugiyaoto M, Johnson F, Evans J and Sharma A 2014 How well do general circulation models represent low-frequency rainfall variability? Water Resour. Res. 50 2108–23
Rogers P and Fiering M B 1986 Use of systems analysis in water management Water Resour. Res. 22 1465–50
Schewe J et al 2014 Multimodel assessment of water scarcity under climate change Proc. Natl. Acad. Sci. USA 111 3245–50
Schlosser C A, Strzpezk K, Gao X, Fant C, Blanc E, Paltsev S, Jacoby H and Reilly J 2014 The future of global water stress: an integrated assessment Earth’s Future 2 341–61
Shen Y, Oki T, Kanai S, Hanasaki N, Usumi N and Kiguchi M 2014 Projection of future world water resources under SRES scenarios: an integrated assessment Hydrol. Sci. J. 59 1775–93
Shukla S and Wood A W 2008 Use of a standardized runoff index for characterizing hydrologic drought Geophys. Res. Lett. 35 L02405
Smit B and Pilifosova O 2003 From adaptation to adaptive capacity and vulnerability reduction Climate Change, Adaptive Capacity Development. pp 9–28
Sperna Weiland F C, van Beek L P H, Kwijdijk J C J and Bierkens M F P 2012 Global patterns of change in discharge regimes for 2100 Hydrology Earth Syst. Sci. 16 1047–62
Stahl K 2001 Hydrological drought—a study across Europe PhD Thesis Freiburger Schriften zur hydrologie (No. 15) Freiburg
Stedinger J R, Vogel R M and Foufoula-Georgiou E 1993 Frequency analysis of extreme events Handbook of Hydrology ed D R Maidment (New York: McGraw-Hill) pp 1–18
Straatmans M et al 2014 Bridging the climate–induced water gap in the twenty-first century: adaptation support based on water supply, demand, adaptation and financing Geophys. Res. Abstr. 16 EGU2014–10641
Tallaksen L M 2000 Streamflow drought frequency analysis Drought and Drought Mitigation in Europe (Advances in Natural and Technological Hazards Research vol 14) ed J V Vogt and F Somma (Dordrecht: Kluwer) pp 103–17
Tallaksen L M, Madsen H and Hidral H 2004 Frequency analysis Hydrological Drought. Processes and Estimation Methods for Streamflow and Groundwater (Developments in Water Sciences vol 48) ed L M Tallaksen and H A J Van Lanen (The Netherlands: Elsevier) pp 199–271
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98
Thorn H C 1958 A note on the gamma distribution Mon. Weather Rev. 86 117–22
Timonina A, Hochrainer-Stigler S, Pilgug G, Longman B and Rojas R 2015 Structured coupling of probability loss distributions: assessing joint flood risk in multiple River Basins Risk Anal. 35 2102–19
Turner S W D, Blackwell R J, Smith M A and Jeffrey P J 2016 Risk-based water resources planning in England and Wales: challenges in execution and implementation Urban Water J. 13 182–97
UNISDR 2009 UNISDR terminology on disaster risk reduction Geneva, Switzerland (http://unisdr.org/soe/inform/terminology)
UNISDR 2015 Sendai framework for disaster risk reduction 2015–2030 Geneva, Switzerland (http://unisdr.org/we coordinate/sendai-framework)
van Beek L P H, Wada Y and Bierkens M F P 2011 Global monthly water stress: I. Water balance and water availability Water Resour. Res. 47 W07517
van Huijgevoort M H J, Hazenberg P, van Lanen H A J and Uijlenhoet R 2012 A generic method for hydrological drought identification across different climate regions Hydrolog. Earth Syst. Sci. 16 2437–51
van Vliet M T H, Franssen W H P, Yearsley J R, Ludwig F, Haddeland I, Lenzenmaier D P and Kabat P 2013 Global river discharge and water temperature under climate change Glob. Environ. Change 23 450–64
van Vuuren D P et al 2011 The representative concentration pathways: an overview Clim. Change 109 5–31
van Vuuren D P, Lucas P L and Hilgenrikh H 2007 Downscaling drivers of global environmental change: enabling use of global SRES scenarios at the national and grid levels Glob. Environ. Change 17 114–30
Veldkamp T E, Eijsen S, Wada Y, Aerts J C J H and Ward P J 2015a Sensitivity of water scarcity events to ENSO driven climate
variability at the global scale Hydrol. Earth Syst. Sci. 19
4081–98
Veldkamp T I E, Wada Y, de Moel H, Kummu M, Eisner S, Aerts J C J H and Ward P J 2015b Changing mechanism of
global water scarcity events: impacts of socioeconomic
trends and inter-annual hydro-climatic variability Glob.
Environ. Change 32 18–29
Vicente-Serrano S M, Beguería S and López-Moreno J I 2010 A
multi-scalar drought index sensitive to global warming: the
standardized precipitation evapotranspiration index—SPEI
J. Clim. 23 1696–718
Vörösmarty C J, Green P, Salisbury J and Lammers R B 2000 Global
water resources: vulnerability from climate change and
population growth Science 289 284–8
Vörösmarty C J, Hoekstra A Y, Bunn S E, Conway D and Gupta J
2015 Fresh water goes global Science 349 478–9
Wada Y, van Beek L P H and Bierkens M F P 2011 Modelling global
water stress of the recent past: on the relative importance of
trends in water demand and climate variability Hydrol. Earth
Syst. Sci. 15 3785–808
Wada Y, van Beek L P H, Wanders N and Bierkens M F P 2013
Human water consumption intensifies hydrological drought
worldwide Environ. Res. Lett. 8 034036
Wada Y, Gleeson T andarnault L 2014a Wedge approach to water
stress Nat. Geosci. 7 615–7
Wada Y, Wisser D and Bierkens M F P 2014b Global modeling of
withdrawal, allocation and consumptive use of surface water and
groundwater resources Earth Syst. Dyn. 5 15–40
Wada Y et al. 2016 Modeling global water use for the 21st century: the
Water Futures and Solutions (WfS) initiative and its
approaches Goshc. Model Dev. 9 175–222
Ward P J, Eisner S, Flörke M, Dettinger M D and Kummu M 2014a
Annual flood sensitivities to El Niño–Southern oscillation at
the global scale Hydrol. Earth Syst. Sci. 18 47–66
Ward P J, Jongman B, Sperna Weiland F, Bouwman A, van Beek R,
Bierkens M F P, Litgvoet W and Winsemius H C 2013
Assessing flood risk at the global scale: model setup, results,
and sensitivity Environ. Res. Lett. 8 044019
Ward P J, van Pelt S C, de Keizer O, Aerts J C J H, Beersma J J,
vanderf Hurk B J M and te Linde A H 2014b Including
climate change projections in probabilistic flood risk
management J. Flood Risk Manag. 7 141–31
Warszawski L, Friele K, Huber V, Piontek F, Serdeczny O and
Scheve J 2014 The inter-sectoral impact model
intercomparison project (ISI–MIP): project framework Proc.
Nat. Acad. Sci. 111 3228–32
Weedon G P, Balsamo G, Bellouin N, Gomes S, Best M J and
Viterbo P 2014 The WFDEI meteorological forcing data set:
WATCH Forcing data methodology applied to ERAInterim
reanalysis data Water Resour. Res. 50 2650–14
Weedon G P, Gomes S, Viterbo P, Shuttleworth W J, Blyth E,
Osterle H, Adam J C, Bellouin N, Boucher O and Best M 2011
Creation of the watch forcing data and its use to assess global
and regional reference crop evaporation over land during the
twentieth century J. Hydrometeorol. 12 823–48
Wilks D S 1990 Maximum likelihood estimation for the gamma
distribution using data containing zeros J. Clim. 3 1495–501
Wilks D S 1995 Statistical Methods in Atmospheric Sciences: An
Introduction (San Diego, CA: Academic) p 1995
Winsemius H C, Aerts J C J H, van Beek L P H, Bierkens M F P,
Bouwman A, Jongman B, Kwadijk J, Lucas P L, van Vuuren D P and Ward P J 2013 Global drivers of future
river flood risk Nat. Clim. Change (doi:10.1038/nclimate2893)
Wutich A, White A C, White DD, Larson K L, Brewis A and
Roberts C 2014 Hard paths, soft paths or no paths: Cross-
cultural perceptions of water solutions Hydrol. Earth Syst. Sci. 18 109–20
Young R A 2005 Determining the Economic Value of Water: Concepts
and Methods Resources For the Future Washington, DC, USA
p 357