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Water Scarcity:
Insufficient Supply from Rivers and Streams

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pbl.nl/future-water-challenges

Main messages

- Areas with a high water scarcity risk, both now and in the future, are predominantly located in the Middle East, Southeast Asia, and northern Africa;
- The relatively high level of water scarcity risk in the Netherlands, found as a result of the approach chosen for this study, highlights the country's dependence on incoming freshwater resources from upstream areas (e.g. the Rhine and the Meuse), as well as its dependence on international trade and the corresponding virtual water flows;
- The water scarcity risk is expected to intensify worldwide between 2010 and 2050, irrespective of climate change and/or socio-economic developments;
- Both climate change and socio-economic developments have been shown to exert a significant influence on future water scarcity risk;
- When looking at water scarcity hotspots, socio-economic development is a slightly more important driver of the increase in future water scarcity risk for Asia and Africa, but in regions with lower population growth rates, climate change is the dominant driver;
- The overlap in risk levels for flooding and water scarcity related to surface runoff is particularly prevalent in Sudan, Pakistan, Bangladesh, and Rwanda.

1.1.1 Introduction

Water scarcity, the inability of water resources to meet water demand (Young, 2005; Hanemann, 2006; Rijsberman, 2006), is considered to be one of the most important global risks for society (Howell, 2013). In recent decades, changes in hydro-climatic conditions along with socio-economic developments have aggravated water scarcity conditions both globally and regionally (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., 2015). Projected increases in water demand due to changing lifestyles and a growing population, as well as projected changes in hydro-climatic conditions, are expected to further increase both the probability of water scarcity events, as well as their societal impact (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; Schlosser et al., 2014; Wada et al., 2014a; Kiguchi et al., 2015).

Risk assessment methods applied in water scarcity research facilitate the inclusion of variability and provide insight into the severity, distribution, and impact of both high and low probability of water scarcity events. This can be achieved using probabilistic approaches (Paté-Cornell, 2012; Hall and Borgomeo, 2013; Ward et al., 2014) 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).

This background document focuses on freshwater supply from rivers and streams.

The scarcity of water supplied from rivers and streams has a **direct** impact on a number of Sustainable Development Goals:

- SDG 1. No poverty: too little water means that food production is limited and the economy in general is affected. This is not the case, however, for countries such as the Gulf States that are rich enough to import food and products, and to make drinking water through desalination.
- SDG 2. Zero hunger: water scarcity may lead to crop yield loss, affect the food supply, and lead to hunger in countries that mainly rely on producing their own food and are not rich enough to import food from the global market.
- SDG 3. Good health and well-being: too little water supplied from rivers and stream, generally, leads to a relatively high level of pollution of the available resources, and diseases spread more easily.
- SDG 6. Clean water and sanitation: similar to SDG 3 (above).
- SDG 13. Climate action: climate change is an important driver, further increasing water scarcity in regions that are already water stressed.

The scarcity of water supplied by rivers and streams also has an **indirect** impact on a number of Sustainable Development Goals:

- SDG 8. Decent work and economic growth: sufficient, clean fresh water is the basis for all economic processes.
- SDG 11. Sustainable cities and communities: an insufficient supply of fresh water makes it hard for cities to be sustainable, while it is particularly in these cities that sustainability is most important. In particular, too little fresh water often leads to overexploitation of groundwater reserves, which in turn affects the sustainability of the physical environment.
- SDG 15: Life on land: when water is scarce, the local human population will use most of it, leaving little for biodiversity. In addition, biodiversity also suffers from the overexploitation of groundwater reserves.
- SDG 16. Peace, justice and strong institutions: water scarcity may lead to conflict as a result of its impact on poverty, hunger and migration, and because downstream regions depend on upstream regions. Furthermore, a large number of the regions in the world where water stress is most severe are often also regions where governance is weak (exceptions being Israel and Jordan).

1.1.2 Objective

The objective of this document is to provide an estimate of global water scarcity with respect to the supply from rivers and streams (surface runoff) for 2010 (the current situation) and 2050, thereby indicating hotspots of risk: regions in the world where water demand cannot be met from water resources supplied by surface runoff. The document provides an assessment of the global water scarcity risk, looking at both present day and future conditions. Water scarcity is defined here by means of the Falkenmark Index or the Water Crowding Index, a simple but often-used indicator that estimates annual water availability per capita (Falkenmark, 1986, 2013; Rijsberman, 2006). In contrast to previous water scarcity assessments, we used probabilistic methods to deal with interannual variability and extremes in the availability of freshwater resources, and express water scarcity risk in terms of the expected annually exposed population (EAEP) to water scarcity, in a given area (Veldkamp et al., 2016). Moreover, the document shows how the risk of water scarcity changes between 2010 and 2050 in different parts of the world, due to a combination of climate and socio-economic changes, expressed in terms of the increase in the number of people affected. In addition, it shows the relative contribution of climate change, and the increase or decrease in population in areas exposed to changes in water scarcity risk.

1.1.3 Methods and Analysis

In this study, we used daily runoff (0.5° x 0.5°) from the global hydrological PCR-GLOBWB model to calculate the availability of water supplied from rivers and streams on an annual basis (Van Beek et al., 2011; Wada et al., 2014b). PCR-GLOBWB uses meteorological forcing data (0.5° x 0.5°), from five global climate models (GCMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and 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 data set (Weedon et al., 2011) using an established method from Hempel et al. (2013). The resulting daily runoff values per RCP were aggregated into annual totals per water province. With water provinces are meant a composite of river basins and administrative regions, which were used throughout this project (Straatsma et al., 2014).

Subsequently, per water province and for each GCM-RCP combination, we fitted a gamma distribution (a statistical distribution that is fitted to the actual data) through two 30-year periods (time slices) of annual water availability: historical (1975–2004) and 2050 (2035–2064). A gamma distribution was used because it is bounded below by zero and therefore capable of reflecting 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 original distribution by using the Kolmogorov–Smirnov or Lilliefors test (Crutcher, 1975; Wilks, 1995; Husak et al., 2007) using P values of 0.001. The gamma parameters were used to estimate annual water availability per water province, for 999 return periods, from 1 up to 1000 years (Wilks, 1990; Stedinger et al., 1993). Water scarcity conditions were expressed using the water crowding index (WCI) (Falkenmark, 1986, 2013; Rijsberman, 2006). The WCI was calculated for each water province as the availability of water for that province for a particular time slice, return period, and in a particular scenario, divided by the population in that time slice, return period, and scenario (see Equation 1):

$$WCI_{i,tp,rp,rcp,ssp} = \frac{WA_{i,tp,rp,rcp}}{P_{i,tp,ssp}} \ (water\ scarcity\ if\ WCI\ \leq 1700), \qquad (1)$$

where $WCI_{i,tp,rp,rcp,ssp}$ is the water availability per capita in water province *i*, time slice *tp*, return period *rp*, climate change projection *rcp*, and socio-economic scenario ssp; $WA_{i,tp,rp,rcp}$ is the total water availability in water province *i*, time slice *tp*, return period *rp*, and climate change projection *rcp*; and $P_{i,tp,ssp}$ is the total population in water province *i*, time slice *tp*, and the *ssp* shared socio-economic pathway.

We used 1700 m^3 per capita, per year, as the threshold for water scarcity (Kummu et al., 2010). The population estimates used in this study to calculate the WCI were derived from the shared socio-economic pathways (SSPs: Van Vuuren et al., 2007, 2011; O'Neill et al., 2012, 2015). The resulting WCI values were plotted on exceedance probability curves. Implementing the threshold of 1700 m^3 per capita, per year, resulted in an exceedance probability impact curve per water province, for each GCM-SSP combination and for each time slice. In this study, we expressed impact as the population exposed to water scarcity events. One should keep in mind, though, that the actual impact of water scarcity is not only influenced by exposure, but also by 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 EAEP (expected annually exposed population). In an exceedance probability impact curve the exceedance probability is plotted on the x-axis, and the impact on the y-axis; the integral yield is the ‘expected’ value. To evaluate what effect the driving forces climate change and population growth each have on the changes in risk levels as we move towards 2050, we repeated the entire risk analysis (Sections 2.1–2.3) with two more runs: (1) a run with transient climatic conditions and fixed (historical) population density conditions; and (2) a run with fixed (historical) climatic conditions and transient population growth conditions.

Figure 1 shows the methodological framework for the assessment of water scarcity risks (expected annually exposed population) in four steps: 1) calculate the annual water availability over the period from 1971 to 2099 using the global hydrological model, PCR-GLOBWB, forced with the output of five global climate models and three representative concentration pathways (RCPs: RCP2.6, RCP6.0, RCP8.5); 2) fit a gamma distribution to the annual water availability data for the different time slices and climate change (RCP) projections; 3) combine the probability density functions of annual water availability with estimates of population density (SSPs: SSP1, SSP3, SSP5) to calculate water scarcity and draw exceedance impact curves for the following scenarios: sustainable development (RCP2.6– SSP1), fragmented world (RCP6.0–SSP3), and fossil-fuel-based development (RCP8.5–SSP5); and 4) estimate water scarcity risk for the different time slices and scenarios.

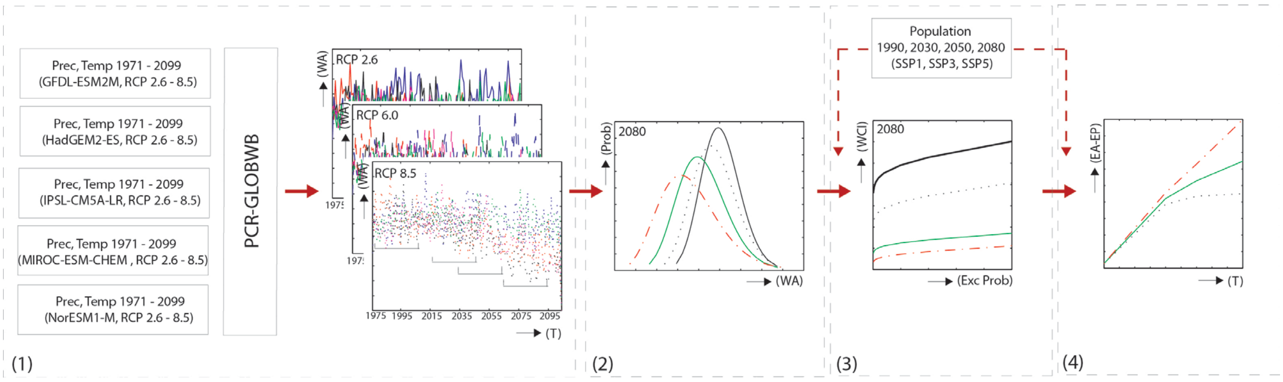

Figure 1: Methodological framework for the assessment of water scarcity risks (source: Veldkamp et al., 2016)

1.1.4 Results

Currently affected population

Figure 2 shows the water scarcity risks for each country, along with the expected annually exposed population expressed as share of the total population of that country, under current conditions. The results for the baseline period show that regions located in the Middle East, Southeast Asia, and northern Africa have a relatively high risk of water scarcity. When expressing water scarcity risks in terms of absolute population estimates, the majority of affected people can be found in Southeast Asia (not visualised here). At country level, as shown here, relatively low water scarcity risk values are found for Australia, North America, and parts of Latin America. However, when interpreting values at country level, one should bear in mind that the aggregation of water provinces to country scale means that some of the variability is lost. In selected sub-regions of these countries, especially those with a relatively high population density, water scarcity risks are in fact significantly higher than the countrywide average risk levels presented in this figure. The relatively high water scarcity risk levels presented in Figure 2, for regions that are located downstream in river basins, such as Egypt, the Netherlands and Belgium, result from the fact that, in the analysis, water availability (in terms of surface runoff) was calculated for water provinces that are restricted by the national borders of these countries. In this study, for instance, runoff in the Netherlands is available for the Dutch population but runoff in Germany is not, even though, in fact, part of the surface runoff in Germany will flow into the Rhine and therefore into the Netherlands. Actual water availability per capita in the Netherlands is much higher, and water scarcity risk in terms of EAEP much lower, than the results presented here: the Netherlands is highly dependent on incoming discharge from upstream areas (the Rhine and the Meuse basin), and on virtual water flows as a result of the country's high dependence on international trade. The water scarcity risk estimates presented in this study are based on the total sum of local runoff per water province and can be considered as a measure of self-sufficiency in terms of water resources compared to a population's water needs, reflected here by the average global water need per capita. One may conclude, therefore, that a country such as the Netherlands has relatively low self-sufficiency in terms of surface water runoff generated in the country itself.

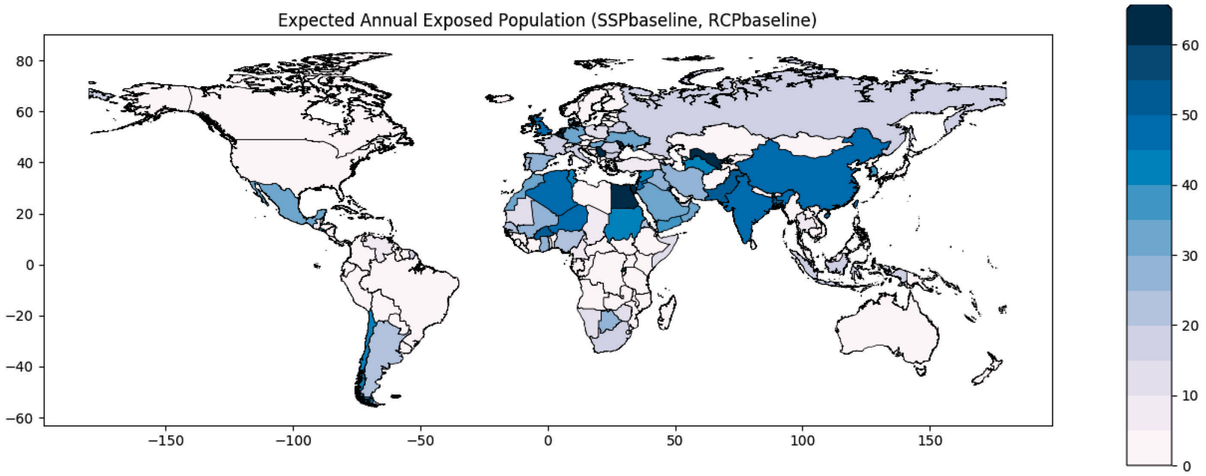

Figure 2: Water scarcity risks per country (expected annually exposed population) expressed as a share of the total population of that country under current conditions (baseline period: 1975–2004).

Changes in risks and hotspots

Figure 3 shows the changes in water scarcity risk towards 2050, in various climate change and socio-economic scenarios: (a) SSP1 – RCP4.5; (b) SSP1 – RCP6.0; (c) SSP2 – RCP6.0; (d) SSP3 – RCP8.5. In all those scenarios, we find an intensification of water scarcity risk (when expressed in relative terms) towards future conditions. When comparing current and future water scarcity risk, expressed in absolute terms, these trends become even more apparent when population growth is incorporated into these estimates (not visualised here). The results do not highlight significant differences in water scarcity risk between hotspots across the various countries, not even when we look at the relative changes in water scarcity risk between current and future periods. In future time periods too, water scarcity risk hotspots dominate in Southeast Asia, the Middle East, and northern Africa. Increases can also be seen in western Europe, although to a lesser extent than in the aforementioned regions. Countries in northern Africa, in particular, are significantly affected by climate change and socio-economic developments. This is highlighted not only by the increase in relative water scarcity risk but also by the relatively wide spatial expansion of water scarcity risk compared to the current time period. Changes in projected water scarcity risk between 2010 and 2050 are relatively small for North America, Russia, northern and eastern Europe, and Australia, especially when it comes to relative values compared to the total population.

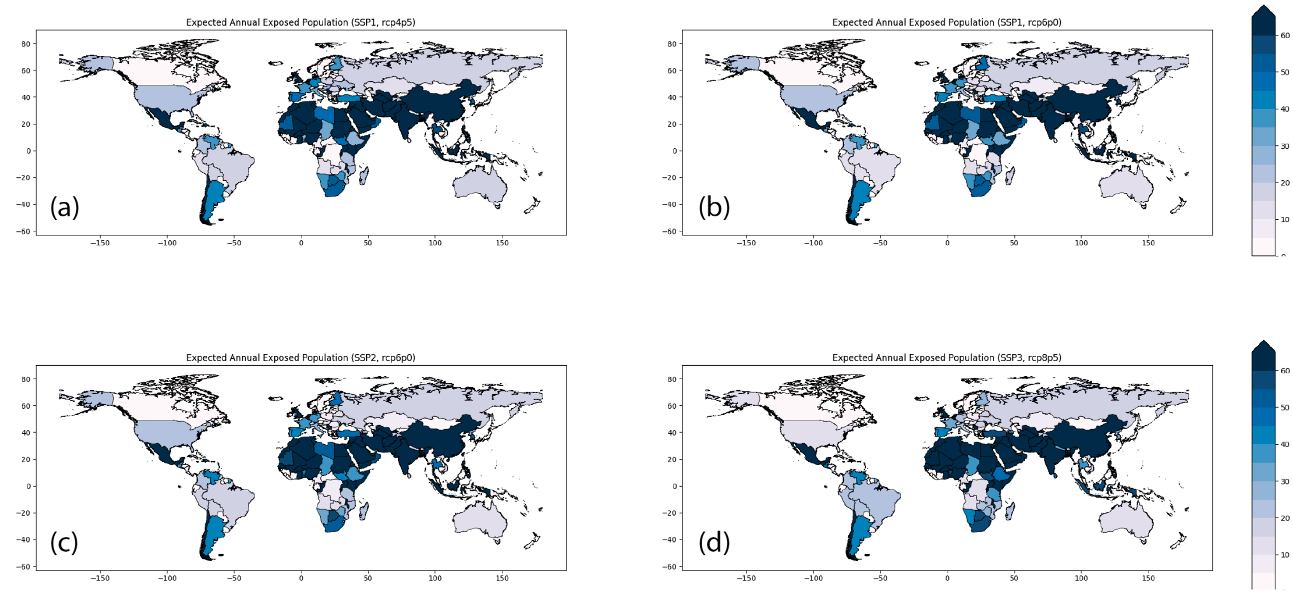

Figure 3: Water scarcity risks (expected annually exposed population) expressed as a share of the total population per country for 2050 in various climate change and socio-economic development scenarios: (a) SSP1 – RCP4.5; (b) SSP1 – RCP6.0; (c) SSP2 – RCP6.0; (d) SSP3 – RCP8.5.

For a selection of hotspot countries, Figure 4 highlights the change in water scarcity risk between 2010 and 2050, in the four climate change and socio-economic development scenarios ((a) SSP1 – RCP4.5; (b) SSP1 – RCP6.0; (c) SSP2 – RCP6.0; (d) SSP3 – RCP8.5). The selection shows the top-20 countries in terms of risk relative to total population. Moreover, it shows the relative importance of climate change and socio-economic developments as drivers of changes in water scarcity risks towards 2050. For these selected hotspots, we found that both climate change and socio-economic developments exert a significant influence on the changes in future water scarcity risk levels, irrespective of the climate change and/or socio-economic development scenario applied. Socio-economic developments are a slightly more important driver of the increase in future water scarcity risk levels than climate change, for Asia and Africa (looking at the water scarcity hotspots). In regions with lower population growth rates (selected regions in Europe), the impact of climate change is slightly more important. The different climate change and/or socio-economic scenarios applied do not seem to significantly influence the relative influence of these drivers of change. For instance, comparing Figures 4a and 4b indicates that shifting from RCP4.5 to RCP6.0 does not significantly influence the change in future water scarcity risks, nor does it influence the relative importance of the identified drivers of change. Comparing Figures 4b with 4c underpins this observation, but then for the impact of socio-economic developments (varying between SSP1 and SSP2).

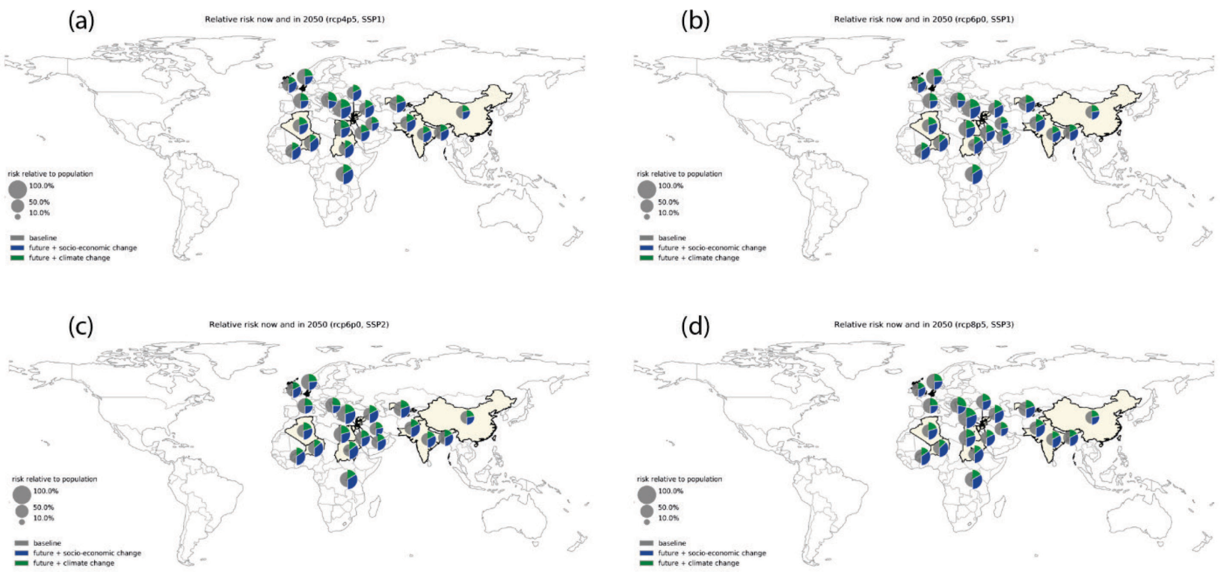

Figure 4: Change in water scarcity risk between 2010 (more precisely: the 1975–2004 baseline period) and 2050 for hotspot countries and the relative importance of drivers of change in various climate change and socio-economic development scenarios: (a) SSP1 – RCP4.5; (b) SSP1 – RCP6.0; (c) SSP2 – RCP6.0; (d) SSP3 – RCP8.5.

1.1.5 Conclusion

Our results show that areas with relatively high water scarcity risks are predominantly found in the Middle East, Southeast Asia, and northern Africa. When expressed in absolute numbers, the results highlight even further the dominant share that Southeast Asian countries have in the global water scarcity risk .

The definition of water scarcity and the calculation method applied in this study do not take account of discharge coming from upstream areas or virtual water flows; this study merely expresses a region's self-sufficiency in terms of the availability of water resources from surface runoff within the country's own national borders. In this way, relatively high water scarcity risks were calculated for countries located downstream in river catchments, such as the Netherlands and Belgium, whereas in reality these risks are alleviated by virtual water flows and incoming discharge. Apart from that, the country scale used for the analysis applied here obscures potentially relatively high water scarcity risk, both regionally and locally. This is especially the case in relatively large countries with a high spatial variation in population density, such as Australia, the United States, Canada, and Brazil.

Taking these considerations into account, we found that there will be a global intensification of water scarcity risk between 2010 and 2050, irrespective of the climate change and/or socio-economic scenario applied. Looking at the dominant drivers of change, we found that both climate change and socio-economic developments exert a significant influence on the changes in water scarcity risk towards 2050, in all the hotspot countries we identified, again irrespective of the climate change and/or socio-economic scenario applied.

Finally, when we compared this 'hotspot' analysis of water scarcity with the analysis carried out for flooding (see background document River Flood Risk), we found a strong overlap in risk for Sudan, Pakistan, Bangladesh and Rwanda. This could have a number of important implications for the impact of flooding events and droughts, both now and in the future, and the development of policy to cope with these hazards.

1.1.6 Discussion

Limitations

In this study we used local runoff as a parameter to estimate the availability of water; it is important to reiterate here that this study does not take account of upstream–downstream relationships between water provinces. To show such relationships would require a separate study, modelling multivariate extreme values using copulas or other statistical techniques (Chung and Salas, 2000; Favre et al., 2004; Hochrainer and Pflug, 2012; Timonina et al., 2015). Such a study should also take into account the impact of upstream water withdrawals in all sectors under the different socio-economic and climate change scenarios applied (e.g. Wada et al., 2016); data that were not yet available when we performed our analysis. In using natural flows, we did not take account of the water resources available from man-made and managed reservoirs, groundwater storage, or from desalination plants; nor did we include any infrastructure for the distribution of water. Water availability values presented in this study should be interpreted as conservative (i.e. lower-end estimates) and therefore lead to higher-end risk estimates. A separate background document discusses water scarcity with respect to groundwater.

Despite the fact that water quality and water quantity conditions are highly interdependent, we did not take account of water quality conditions in this study. A lack of water quality is expected to become more relevant in the future (e.g. Jiang et al., 2014) and could severely limit the availability of freshwater resources. Extending the water scarcity risk assessment framework to incorporate a water quality module would therefore, in all likelihood, increase the water scarcity risk estimates presented in this study. A separate background document discusses water quality.

This study used only one global hydrological model (GHM) to estimate water scarcity risks. 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 generally recommended to use an ensemble of models, as the GHM spread can exert a significant influence on the range of outcomes (Schewe et al., 2014; Döll et al., 2015). The difficulty that GHMs have in modelling water availability in desert areas (Van Huijgevoort 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 only have a minor share of the total global population, one should take account of the fact that the inability to model these regions in an appropriate manner leads to underestimations of risk levels, especially in northern Africa.

For this study, PCR-GLOBWB used meteorological forcing data from five global climate models (GCMs) and was bias-corrected following Hempel et al. (2013). Hempel et al. (2013) showed that the bias-correction method applied could 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 correlation with the observation data set. Hempel et al. (2013) did not, however, correct for interannual variability (Rocheta et al., 2014). A new nested bias-correction method could be adopted in future studies to account for this (Rocheta et al., 2014; Mehrotra and Sharma, 2015).

In this study, risk is expressed in terms of the EAEP to water scarcity. A potentially exposed population, however, does not per se mean that there will be an impact or economic impact. To come to a full risk assessment framework, more work needs to be done on translating risk estimates in terms of exposed population into estimates covering the ‘economic’ impact. A first step should be to incorporate vulnerability, which would include the sensitivity of a population to water scarcity, the available infrastructure and resources (financial and otherwise) to cope with water scarcity, the portfolio of economic activities dependent on the available water resources, the dependence of an economy on local or external water resources, and the capability of the responsible government to deal with water scarcity in a 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). Translating exposure to economic impact is an emerging research field which uses, among other things, hydro-economic models and econometric optimisation routines (Brouwer and Hofkes, 2008; Harou et al., 2009). So far, their application in global risk-based assessments has been limited.

How do the results relate to other relevant studies?

Despite the wide variety of GHMs used, the different climate change projections and socio-economic scenarios applied, plus 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). The use of a gamma distribution to represent the annual availability of water enabled us to use numerous return periods to cover the interannual variability in water availability as well as low probability events that are not normally included (Paté-Cornell, 2012; Hall and Borgomeo, 2013). Compared to 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 results on the estimated water stressed population or regions (Gosling and Arnell, 2013; Veldkamp et al., 2015). This becomes particularly important when moving from global, to regional, to local water scarcity risk estimates.

In line with earlier studies (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), we found that global and regional water scarcity risk increases towards 2050. Moreover, the results show that population growth outweighs the impact of climate change, globally and regionally, in all scenarios. At local scales, we found population growth to be the largest driver of change in the majority of water provinces in, for instance, the Fragmented World scenario. In the fossil-fuel-based development scenario, however, we found that the changes in risk levels are predominantly driven by climate change, in the majority of water provinces. The results show that disaggregation to different spatial scales is important. For example, in large countries, where values are averaged across many water provinces, high water scarcity may exist in some regions but this cannot be seen when averaged to country scale. Moreover, the use of country boundaries in defining water basins means that river basins are split into different units. Hence, the use of a single scale could obscure water scarcity problems at other scales and thus hamper the evaluation of potential underlying causes (Hering et al., 2015; Vörösmarty et al., 2015).

Adaptation strategies

It is to be expected that, between now and 2050, adaptation strategies will become more widely available and they will be based on new technologies that reduce the impact of water scarcity. These strategies will be addressed in the background document on water scarcity related to groundwater reserves.

1.1.7 Gaps and recommendations for future research

A number of recommendations for future research can be made based on the work presented in this study:

- Expand the analysis from using only local runoff to include incoming discharge and alternative freshwater sources (e.g. groundwater use, desalinisation). Including upstream/downstream dependencies will enable us to give a more realistic representation of the actual shortages in freshwater resources compared to demand (Veldkamp et al., 2017). The definition of water scarcity in that sense is not a proper measure of self-sufficiency but merely an indication of a country's level of dependence on other neighbouring countries for its freshwater supply. The same holds for the inclusion of virtual water flows associated with trade.
- Account for water quality issues as they are a limiting factor in the use of the freshwater resources that are available and therefore have a potentially significant impact on water scarcity.
- Expand the analysis by using multiple global hydrological models in order to get an insight into the robustness of the results from the chosen global hydrological model.
- Incorporate a measure of vulnerability or resilience in order to establish the actual impact of water scarcity, rather than just the potential exposure to water scarcity. Not all countries, regions, or parts of populations are equally vulnerable to a shortage in the availability of freshwater resources. In order to present a more informative picture on the 'actual' impact of water scarcity (e.g. economic impact or potential fatalities) it is important to include a society's vulnerability or resilience to water scarcity. Work is being done on the development of such sub-national vulnerability maps, e.g. by combining information from the UN human development indicators (mapping the level of inequality, level of education, level of trust in government policy and management) with statistics on GDP, poverty rates and sectoral economic dependencies. More work is to be done here, however, to combine such data sets with hazard maps to come to more sophisticated risk assessments.
- Include future water demand projections to assess demand-driven water stress (i.e. assuming that people and sectors have changes in their demand for water). This would enable the characterisation of future trajectories of change in water scarcity (see also Kummu et al., 2016) in future scenarios. The different pathways of change (e.g. water stress first, water shortage first, only water stress, only water shortage) would call for different adaptation strategies (focusing on water supply or water demand) and would result in varying portfolios of adaptation.
- Being able to simulate the feedback linkages between meteorological, hydrological, and socio-economic conditions will become increasingly important in evaluating water scarcity, both currently and in the future. More work is required in order to incorporate these feedback linkages into the modelling frameworks that are applied in global water scarcity assessments.
- In real-life, people and stakeholders do not always act in an economically rational way, but this has not yet been included in an appropriate way in global studies. The limited inclusion of an economic rationale that accurately represents agents' preferences and responses remains a weakness when evaluating the effectiveness of adaptations to water scarcity. Future research should therefore attempt to use methods to represent agents' preferences and responses, for example using agent-based models.

- Because of the limited validation options, it is often unclear how various drought and water scarcity indicators differ with respect to their applicability, usability, and representativeness of drought and/or water scarcity events, and which indicator best serves a specific problem, context, or risk management or decision-making target. A global systematic inventory and comparative assessment of tools to model drought and water scarcity risk, evaluating not only their ability to identify drought and water scarcity events at regional and local scales, but also their ability to accurately represent the impact of drought and water scarcity when compared to local impact-based observations, would provide more insight into the representativeness and usefulness of these global indicators and facilitate the correct application and operationalisation of these tools at regional and local levels.

1.1.8 References

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