3. Critical review of climate impact modelling on water resources

Computer models are invaluable tools for the estimation of climate change and its associated impacts on water resources. However, uncertainties along the impact model chain are a major challenge in assessing the hydrologic effects of climate change. Sources of uncertainty include Global Climate Models (GCMs), GHG emission and concentration scenarios (e.g. Representative Concentration Pathways (RCPs)), downscaling methods, and hydrological models. This chapter introduces the modelling of climate change and its associated impacts. Furthermore, it discusses possible sources of (projection) uncertainty and their relevance for the assessment of water resources, availability and hydrological extremes, both now and in the future. At the end of the chapter, options for improving the underlying data in order to increase the robustness of hydrological impact assessments are presented.

Key Messages of Chapter 3

- Despite advances in climatological and hydrological modelling, significant uncertainties regarding the specific impacts of climate change on water resources remain.
- GCMs, hydrological models and scenarios of future GHG concentrations (e.g. RCPs) contribute to uncertainties associated with climate change impact projections for the water sector.
- Individual contributions by uncertainty sources may change under different hydro-climatological conditions with respect to both spatial (e.g. different altitudes) and temporal patterns (e.g. dry vs. wet season).
- In order to improve hydro-climatic data – in terms of quantity and quality – it is necessary to increase the coverage of hydro-meteorological monitoring networks, ensure the necessary maintenance of existing stations and set up efficient data quality control procedures. As a consequence, information and subsequent applicability for end-users could improve the robustness of hydrological model projections.
- There is a strong demand for improved hydro-climatic information, such as interlinked in situ and remotely sensed data, e.g. from satellites and socio-economic data, for instance on land and energy use, which may further improve future scenarios.
- Some uncertainties will inevitably remain, thus, creating further challenges for development as well as adaptation strategies.

Definition of terms

Adaptation
"The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities".[a]
Generally, adaptation measures can reduce the risk by reducing vulnerability and in certain cases also exposure. Vulnerability can be reduced either by decreasing sensitivity or by increasing capacity.[b]

Adaptive capacity
The combination of the strengths, attributes, and resources available to an individual, community, society, or organization that can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities.[a,c]

Climate variability
"refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)".[a]

Exposure
"The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected." [a]

Flexible adaptation plans
Flexible adaptation plans allow decision-makers to select a course of action to adjust to shifting or emerging conditions while ensuring a near-term action does not rule out potentially critical future actions. Flexible plans cope with uncertainty by adapting to changing conditions (some times referred to as adaptive management).[a, b, c]

Hazard
"The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts".[a]

No/low-regret
"In the absence of accurate climate prediction models, the "no-regret" or (perhaps more aptly named "low-regret") approach gives priority to actions that are prudent regardless of future climate conditions." [b]

Robustness
The ability of a system to remain functioning under a large range of disturbance magnitudes.[c] In addition to being a characteristic of a system, robustness can also be a characteristic of decision making itself (e.g., robust decision making), meaning a plan is performing well across a large range of uncertainties.[b]

Resilience
The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions. [a, c]

Risk
The likelihood over a specified time period "for consequences [= impacts] where something of value is at stake and where the outcome is uncertain. [...] Risk results from the interaction

of vulnerability, exposure, and hazard".[a]

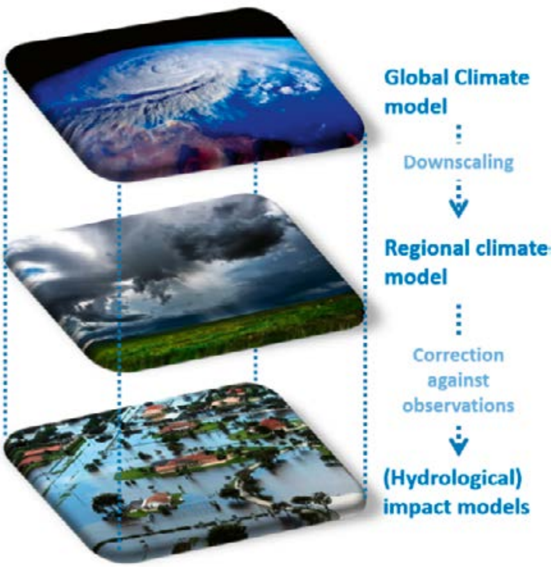
Uncertainty An expression of the degree to which a value or relationship is unknown. Uncertainty "can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts)".[a]

Vulnerability "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt".[a]

3.1 Introduction to climate change impact modelling

Climate models are essential tools to understanding and quantifying climate variability, climate change, and related impacts (IPCC, 2013). In climate change impact modelling, a chain of computer models translates global scenarios for GHG emissions and atmospheric concentrations into regional impacts, such as effects on water resources, hydrological processes and extremes (e.g. floods and droughts). A simplified model chain is shown in *Figure 2 (left)*.
The chain begins with the physically-based Global Climate Models (GCMs), whose results are transformed into regional climate and weather simulations by statistical means or physically based regional climate models – a process also called "downscaling".

Global Hydrological Models (GHMs) are mostly driven directly by global climate model output, after the correction of systematic errors ("bias-correction" against observations). **Regional Hydrological Models (RHMs)** are usually driven by regional climate model outputs. In most cases, this also includes a bias-correction of the climate data. Additional spatial information is needed to initialize a hydrological model in order to take into account specific regional features of the catchment area, such as soil and geological characteristics, land use, surface elevation, as well as land and water management (optional): *see Figure 2 (right)*.



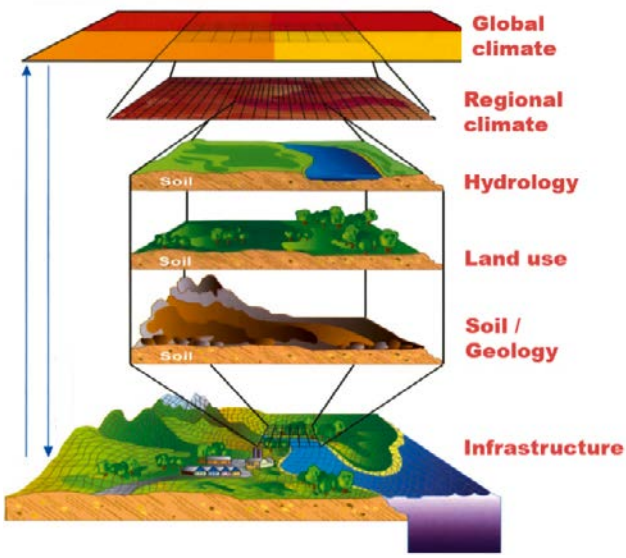


Figure 2 (left): Simplified model chain from global climate to regional impact models.

Figure 2 (right): Layers of information applied in climate impact models (Hadley Climatic Research Unit, changed).

Global socio-economic scenarios and GHG concentration pathways can be imagined as stories of possible futures describing factors that are difficult to quantify or determine, such as governance, social structures, institutions, and GHG emissions. In different forms, these have been a basis for the regularly published Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC), which provide a summary of the current scientific, technical, and socio-economic understanding of climate change and its associated impacts.

The present report uses the latest scenarios as defined for the IPCC's Fifth Assessment Report (AR5), namely, **Representative Concentration Pathways (RCPs)**. RCPs do not constitute socio-economic scenarios but project the development of radiative forcing at the end of the 21st century (van Vuuren et al., 2011). In consequence, higher amounts of GHG emissions throughout this century relate positively to radiative forcing values. The IPCC AR5 relies on the following four RCPs (IPCC, 2013):

- **RCP2.6:** Radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines;
- **RCP4.5:** Radiative forcing is stabilised at approximately 4.5 W/m^2 after 2100;
- **RCP6.0:** Radiative forcing is stabilised at approximately 6 W/m^2 after 2100;
- **RCP8.5:** Radiative forcing exceeds 8.5 W/m^2 by 2100 and continues to rise.

Radiative forcing refers to changes in Earth's energy budget (the balance of incoming and outgoing radiation) at the top of the atmosphere (IPCC, 2013). For instance, scenario RCP8.5 assumes an increase in radiative forcing, exceeding 8.5 W/m^2 by the end of the century relative to pre-industrial levels. In many studies, including this report, the most extreme scenarios (namely, the low-concentration RCP2.6 and the high-concentration RCP8.5) are analysed under the assumption that their investigation will cover a broad range of possible impacts associated with future climate change.

Climate models translate the RCPs into climate change signals. In this context, AR5 relies heavily on the **Coupled Model Intercomparison Project, Phase 5 (CMIP5)** (Taylor et al., 2013), which provides the results for an ensemble of GCM applications. The outcomes of five selected CMIP5 models were used in the **Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)** (Warszawski et al., 2014) to run hydrological models and quantify climate change impacts for the water sector. The results of CMIP5 and ISIMIP are also used for the analyses performed in the present report.

In addition to the RCPs, researchers have recently developed **Shared Socioeconomic Pathways (SSPs)** in order to include narratives of future socio-economic developments (Riahi et al., 2017). There are five SSP narratives, ranging from a future in which the world focuses on sustainable development, to a middle road, to a future marked by inequality and fossil-fuel intense development. RCPs and SSPs were combined to form a matrix of possible future pathways characterized by a certain climate forcing and associated socio-economic development, e.g. a pathway of 2.6 W/m^2 radiative forcing until the end of the twenty-first century under sustainable development, a pathway of 6.0 W/m^2 in a world characterized by inequality, and so on. The SSPs are being considered for the sixth CMIP phase (CMIP6), which will be the basis of the next IPCC report (AR6) that is expected to be published in 2021-2022 in several parts.

Tools

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)

Until recently, the scientific knowledge about expected climate change impacts remained to a large extent fragmentary. Many studies have analysed potential impacts on specific regions and sectors, and scientists have published numerous papers on this issue. However, the studies were mostly undertaken using different climate scenarios and impact models, an approach that complicates direct comparisons and quantitative syntheses of impacts together with a consistent estimation of uncertainties.

Consequently, ISIMIP was launched in 2013 as a community-driven modelling effort to bring together impact modellers across sectors and scales. The goal was to create consistent and comprehensive projections of impacts of different levels of global warming (https://www.isimip.org/; see Warszawski et al., 2014). ISIMIP offers a framework and protocol for a consistent analysis of climate change impacts across affected sectors and spatial scales. In this way, an international network of modellers contributes to a comprehensive and consistent picture of the world under different climate change scenarios. Within the first phase of ISIMIP, an intercomparison of multiple global impact models driven by climate projections for different emission scenarios was initiated, covering various sectors, including the water sector (e.g. Haddeland et al., 2014; Schewe et al., 2014; Prudhomme et al., 2014; Hattermann et al., 2017), agriculture, biomes, etc.

One can use both global-scale and regional-scale (or river basin-scale) models to assess climate change impacts on hydrological processes. Global-scale modelling studies provide global overviews on impacts and inform policy-makers. However, global-scale modelling outputs are often not reliable at the regional or local scale. Consequently, projections of climate change impacts should be accompanied by studies conducted at the regional scale.

The objective of the intercomparison of multiple impact models is to compare projected climate change impacts and quantify uncertainties from different sources in a systematic way. This strategy leads to more robust results and constitutes a sound basis for the development of adaptation and mitigation strategies. Furthermore, the intercomparison of regional-scale impacts for one sector can contribute to the integration of impacts for specific regions, when results for different sectors are combined.

Most of the results shown in Chapters 4 and 5 of this report were published in the context of ISIMIP and have been complemented by selected additional recent publications.

3.2 Sources of uncertainty in projections of climate change impacts

The top-down flow of information from RCPs over global and regional climate models towards regional impacts induces a **cascade of uncertainty**. This arises as uncertainty from one layer is transferred to the next and thereby picks up that next layer's individual uncertainty, eventually resulting in a multitude of combined uncertainties at the bottom of the cascade (Wilby and Dessai, 2010). It is difficult to account for such uncertainties and thus decision-makers often have trouble interpreting the implications for projections of future climate change impacts. Therefore, researchers use different strategies to aggregate the information about uncertainties (Smith et al., 2018).

Furthermore, also GCMs and GHMs can be major sources of uncertainties. Both model groups add their own contributions of inherent uncertainty during their application. To address this circumstance researchers commonly employ ensembles of models instead of single ones. However, often it remains difficult to assess which model stage (i.e. GCMs or GHMs) contributes the lion's share of total uncertainty in an individual case. *Figure 3* provides an overview of different sources of uncertainty in climate impact modelling on water resources, namely GHG concentration pathways, GCM and GHM, and suggests some actions for uncertainty reduction.

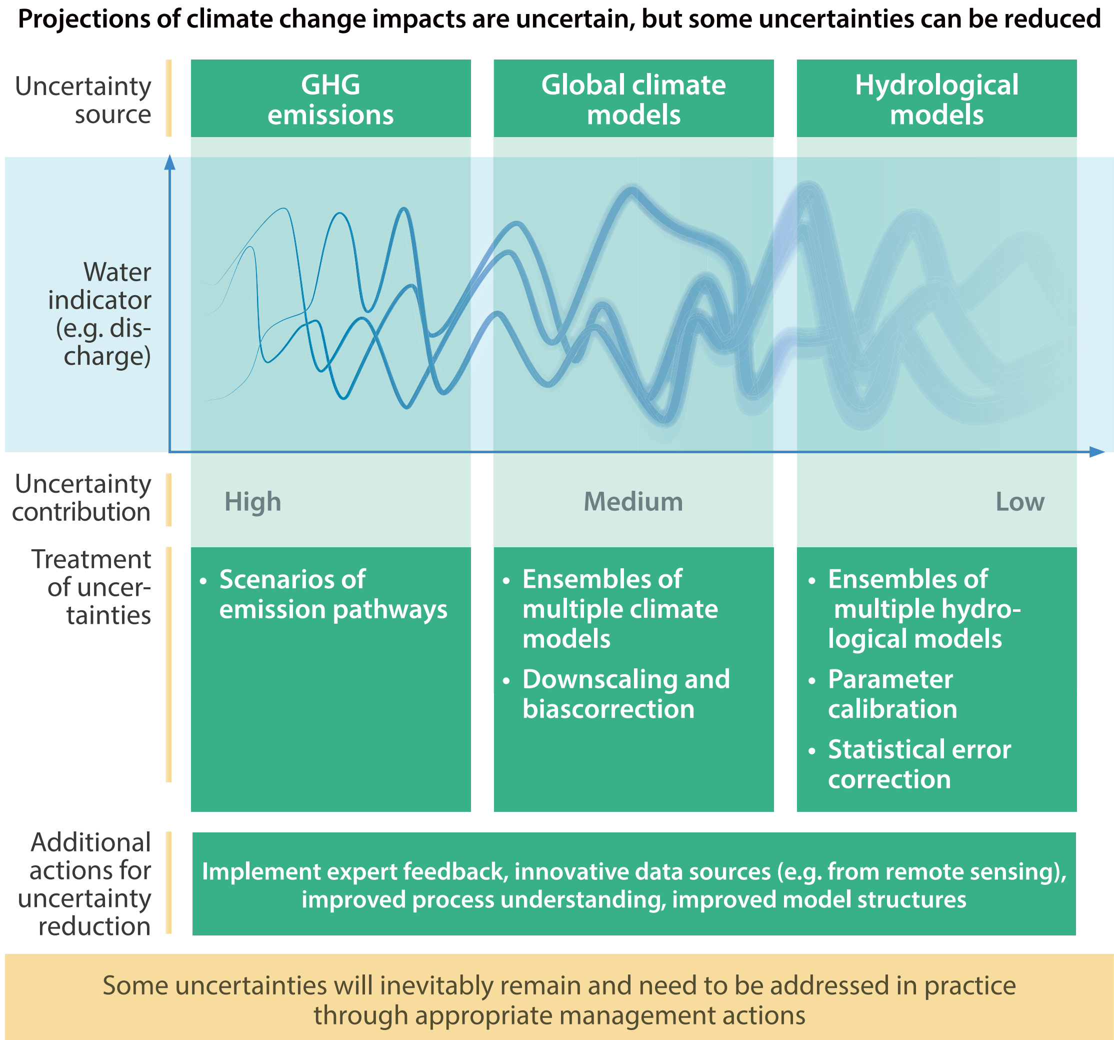


Figure 3: Overview of major sources of uncertainty in climate change impact modelling.

➔ *Shares of uncertainty sources vary according to region and season.*

There is a relation between the shares of GCM and GHM as sources for uncertainty and the regional application of these models. These shares may regionally vary across different parts of the world, as Schewe et al. (2014) found (*Figure 4*). Their results indicate that GCM uncertainty is particularly high in tropical and northern regions, which are characterised by high amounts of precipitation, while in rather dry sub-tropical and arid regions, GHMs are responsible for the lion's share of the uncertainty of projections. Hattermann et al. (2018) found that GCM uncertainty is often even larger than the influence of the selection of a specific GHG concentration scenario.

In addition, uncertainty contributions may vary depending on the time of year. As such, uncertainty attributed to the hydrological model can be considerable in times when the hydrological processes largely determine river discharge. In dry periods, evapotranspiration and groundwater processes dominate the river discharge pattern, and the different hydrological models use different formulations to determine the impact of these processes (Hattermann et al., 2018; Hagemann et al., 2013). This is also the case for snow melt processes (Gelfan et al., 2017).

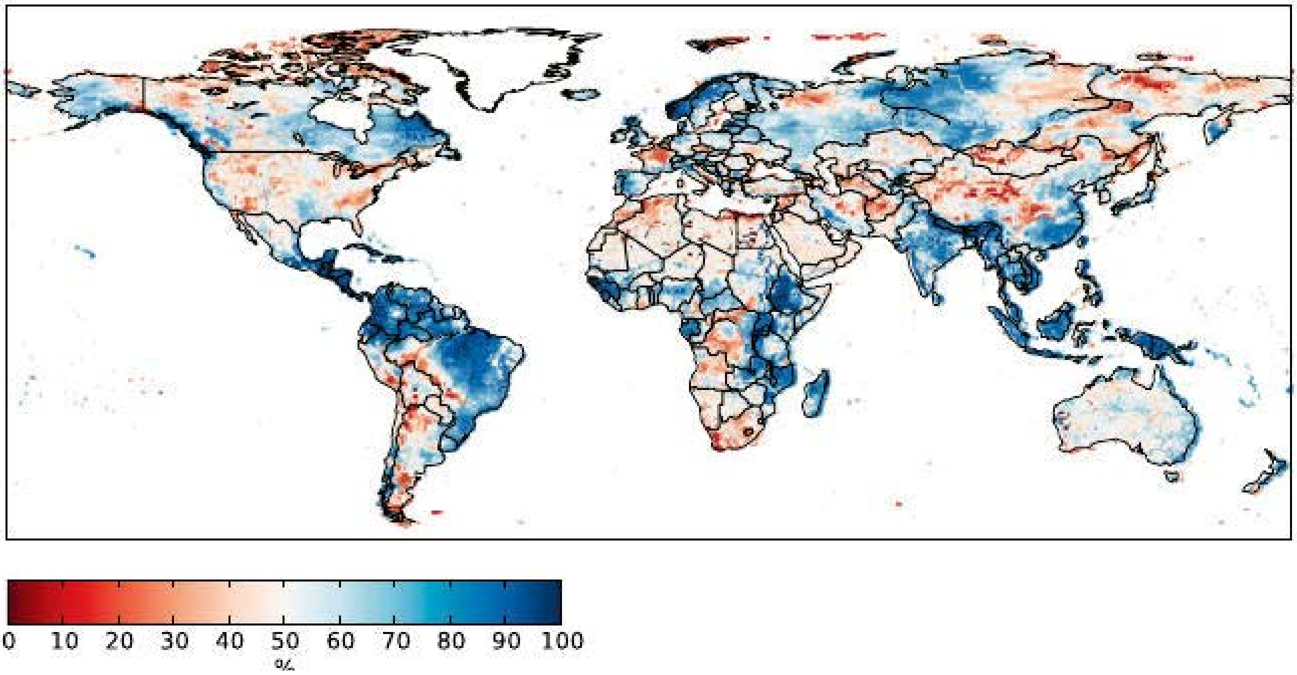


Figure 4: Ratio of GCM variance to total variance as a measure of uncertainty. In red areas, GHM uncertainty predominates, and in blue areas, GCM uncertainty predominates. Greenland has been masked. (Schewe et al., 2014)

3.3 Development and improvement of databases and methods

The potential for uncertainty reduction depends on the respective source of uncertainty. While potential in the field of GHG concentration scenarios is low, due to a lack of clarity concerning future developments, climate models have a larger share of potential in this regard – and hydrological models may be even more promising. Both model groups would certainly benefit from an improved understanding of processes and, as a result, from an improved implementation of the models, as well as enhanced computational resources. In general, improved methods for downscaling and bias-correction could enhance local impact projections. This holds especially true for the analysis of extreme values (e.g. extreme precipitation and flood events), which are often poorly reflected by global models and further distorted by insufficient bias-correction schemes. Moreover, adequate model parameter calibration and the validation of modelling results could also improve the performance of hydrological models. However, regarding calibration and validation, it is essential to have enough high-quality data available.

In order to improve data quantity and quality, it is necessary to increase the coverage of hydro-meteorological monitoring networks, ensure the necessary maintenance of existing stations and set up efficient data quality control procedures. Improving data quality and quantity will increase the robustness of hydrological impact assessments. However, observation density and data quality in meteorology, hydrology, land cover and use as well as socio-economic figures are often limited in many of the countries that are particularly vulnerable to climate change impacts. Furthermore, in many regions, storage of water in snow and ice characterises the water cycle, eventually determining the water supply. Yet monitoring networks are often underdeveloped at the high altitudes where snow and ice are of particular importance.

The development of well-maintained databases is an important pre-condition for climate scenario and impact research. This requires making use of innovative data sources (e.g. remote sensing or crowd-sourced data), the ongoing collection of new data, the sustainable maintenance of existing monitoring networks and ideally the availability or recovery of long-term historical data. In general, data suitable for impact modelling should be quality-controlled, standardised, combined with spatially and temporally complementary data, if available, and digitised in an accessible and shareable format in case the data is only available on paper.

Maintaining such databases in the long term requires strong national and local ownership for data collection, processing, and storage. On the other hand, collaboration with international agencies, such as the World Meteorological Organization (WMO), is advised in order to ensure compliance with international standards, the exchange of data and knowledge, and the development of regional capacities.

➔ *To enhance datasets, a combination of in situ and remote sensing assessments is needed. Available data should be integrated into databases with user-friendly interfaces.*

An important element in the creation of hydrological and meteorological datasets is the interlinking of in situ and remote sensing observations, e.g. through satellites. This is highly important especially in developing countries, where ground-based observational networks often do not cover all regions. Combining various data gathering methods, such as remote sensing and in situ, can lead to significant improvements in observation density, and thus more suitable data for climate impact modelling.

In the long run, one major aim with respect to newly gathered or available data should be their integration into preferably freely accessible databases with user-orientated interfaces. Hence, processing and providing information to interested users (e.g. in the agriculture, energy, water planning, aviation, and education sectors) is one of the most important tasks in this context. This requires strengthening of agency capacities at the national and even regional levels, such as training personnel and improving infrastructure, including in the IT sector. Support for more user-oriented data applications could, for example, be delivered in the form of advice, examples for good practices, as well as warning and forecasting products, including seasonal forecasting. These user-oriented applications should support climate change adaptation planning and the development of cross-sectoral adaptation strategies.

However, even with improved data, some uncertainties about future developments will inevitably remain. This presents challenges for the development of adaptation strategies in water-related sectors and demands appropriate management actions.

3.4 References

Coumou, D., Lehmann J., and Beckmann J. (2015): **The Weakening Summer Circulation in the Northern Hemisphere Mid-latitudes. Science, 348 (6232), 324-327**, DOI: *https://doi.org/10.1126/science.1261768*

García, L.E., Matthews, J.H., Rodriguez, D.J., Wijnen, M.,DiFrancesco, K. N., and Ray, P. (2014): **Beyond Downscaling: A Bottom-Up Approach to Climate Adaptation for Water Resources Management. AGWA Report 01. Washington, DC: The World Bank.**

Gelfan, A., Gustafsson, D., Motovilov, Y., Arheimer, B., Kalugin, A., Krylenko, I., and Lavrenov, A. (2017): **Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues. Climatic Change, 141 (3), 499-515**, DOI: *https://doi.org/10.1007/s10584-016-1710-5*

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z. D., Wada, Y., and Wisser D. (2014): **Global water resources affected by human interventions and climate change. PNAS, 111 (9), 3251-3256**, DOI: *https://doi.org/10.1073/pnas.1222475110*

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Hanasaki, N., Heinke, J., Ludwig, F., Voss, F., and Wiltshire, A. J. (2013): **Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth Syst. Dynam., 4, 129-144**, DOI: *https://doi.org/10.5194/esd-4-129-2013*

Hattermann, F. F., Krysanova, V., Gosling, S. N., Dankers, R., Daggupati, P., Donnelly, C., Flörke, M., Huang, S., Motovilov, Y., Buda, S., Yang, T., Müller, C., Leng, G., Tang, Q., Portmann, F. T., Hagemann, S., Gerten, D., Wada, Y., Masaki, Y., Alemayehu, T., Satoh, Y., and Samaniego, L. (2017): **Cross-scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins. Climatic Change, 141 (3), 561-576**, DOI: *https://doi.org/10.1007/s10584-016-1829-4*

Hattermann, F. F., Vetter, T., Breuer, L., Su, B., Daggupati, P., Donnelly, C., Fekete, B., Flörke, F., Gosling, S. N., Hoffmann, P., Liersch, S., Masaki, Y., Motovilov, Y., Müller, C., Samaniego, L., Stacke, T., Wada, Y., Yang, T., and Krysnaova, V. (2018): **Sources of uncertainty in hydrological climate impact assessment: A cross-scale study. Environmental Research Letters, 13 (1), 015006**, DOI: *https://doi.org/10.1088/1748-9326/aa9938*

IPCC (2013): Climate Change 2013: **The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change** by Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.). **Cambridge/New York: Cambridge University Press.**

IPCC (Intergovernmental Panel on Climate Change) (2014): **Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change**, by Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al.(Eds). Cambridge/New York: Cambridge University Press.

Poff, N. L., Brown, C. M., Grantham, T. E., Matthews, J. H., Palmer, M. A., Spence, C. M., ... and Baeza, A. (2016): **Sustainable water management under future uncertainty with eco-engineering decision scaling.** Nature Climate Change, 6(1), 25.

References

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arneli, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., and Stacke, T. (2014): **Hydrological droughts in the 21st century: hotspots and uncertainties from a global multi-model ensemble experiment. PNAS, 111 (9), 3262-3267**, DOI: *https://doi.org/10.1073/pnas.1222473110*

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... , and Lutz, W. (2017): **The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change, 42, 153-168**, DOI: *https://doi.org/10.1016/j.gloenvcha.2016.05.009*

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F. Warszawski, L., and Kabat, P. (2014): **Multimodel assessment of water scarcity under climate change. PNAS, 111 (9), 3245-3250**, DOI: *https://doi.org/10.1073/pnas.1222460110*

Smith, K. A., Wilby, R. L., Broderick, C., Prudhomme, C., Matthews, T., Harrigan, S., and Murphy, S. (2018): **Navigating Cascades of Uncertainty – As Easy as ABC? Not Quite… Journal of Extreme Events, 5 (1), 1850007**, DOI: *https://doi.org/10.1142/S2345737618500070*

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., et al. (2013): **Ground water and climate change. Nature Climate Change, 3 (4), 322-329**, DOI: *https://doi.org/10.1038/nclimate1744*

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K. (2011): **The representative concentration pathways: an overview. Climatic Change, 109** (5), DOI: *https://doi.org/10.1007/s10584-011-0148-z*

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., and Schewe J. (2014): **The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework. PNAS, 111 (9), 3228-3232**, DOI: *https://doi.org/10.1073/pnas.1312330110*

Wilby, R. L., and Dessai, S. (2010): **Robust adaptation to climate change. Weather, 65** (7), **180-185**, DOI: *https://doi.org/10.1002/wea.543*