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Climate Change and Agricultural Development: A Challenge for Water Management

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Abstract

Freshwater-related risks of climate change increase significantly with increasing global temperatures. Globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits, and agriculture and irrigation, as the largest consumers of water globally, are most at risk. This book analyses the potential impacts of climate change on water for agriculture, and the adaptation strategies in water management to deal with these impacts, drawing on global assessments and regional studies.

This chapter introduces the book, sets the scene for research on climate change in agricultural water management, and synthesizes the issues, methodologies and findings in the chapters to follow. Chapters 2 and 3 provide an overview of global assessment of climate change impacts and water requirement for future agriculture. Chapters 4–7 provide analyses of crop water requirements in four case studies in developing countries. Chapters 8 and 9 are studies of irrigation management under sea-level rise in Vietnam's Mekong Delta. Chapters 10–12 discuss examples of adaptation alternatives such as water-saving techniques and groundwater exploitation, and related policy settings. The last chapter links the dominant approach of uncertainty presented in the climate change discourse with policy discussions on climate adaptation strategies.

1.1 Climate Change and Agricultural Water Management

Observational records and climate projections provide abundant evidence that freshwater resources will be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems. Observed global warming over several decades has been linked to changes in the large-scale hydrological cycle such as: increasing atmospheric water vapour content; changing precipitation patterns, intensity and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff (Bates *et al*., 2008). Over the 20th century, precipitation changes show substantial spatial and inter-decadal variability. Since the 1970s, increases in precipitation have been observed over land in high northern latitudes, while decreases have dominated from 10°S to 30°N. Climate model simulations for the 21st century are consistent in projecting trends of increasing annual average river runoff and water availability at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics (IPCC, 2007b). These trends are reconfirmed in the Fifth Assessment Report by IPCC (2013).

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temperatures associated with increasing greenhouse gas (GHG) concentrations. Globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits. By the 2050s, the area of land subject to increasing water stress due to climate change is projected to be more than double that with decreasing water stress (Bates *et al*., 2008). In particular, frequency of short hydrological droughts is likely to increase in the presently dry regions (IPCC, 2014).

Rainfed agriculture is vulnerable to climate change through the direct impacts of changed rainfall and temperature conditions; irrigated agriculture bears the additional risk of changes in availability of surface and groundwater. Irrigation is the largest water consumer globally: about 70% of all freshwater withdrawals go to irrigated agriculture (UN Water, 2009). Increasing water scarcity may limit food production in rainfed systems, putting pressure on food prices and increasing countries' dependence on food imports or investments into irrigation. Shifting from rainfed to irrigated agriculture is a front-line adaptation strategy to hotter, drier conditions, but will in turn increase demand for water. According to FAO (Food and Agriculture Organization for the United Nations) projections, developing countries, with 75% of the global irrigated area, will need to expand their irrigated areas by 0.6% per year until 2030 to meet food demand (Bruinsma, 2003), although a smaller expansion of irrigated area is assumed under all four scenarios of the Millennium Ecosystem Assessment, with global growth rates of only 0–0.18% per year until 2050 (Millennium Ecosystem Assessment, 2005).

Regarding crop water requirement, the physiological effect of CO_2 is associated with an increased intrinsic water use efficiency of plants, which means that less water is transpired per unit of carbon assimilated (IPCC, 2014). For C3 plant species, including most food crops, the CO_2 effect may be relatively greater for crops that are under moisture stress compared to well-irrigated crops. The large-scale implications of CO_2–water interactions (i.e. at canopy, field and regional level) are highly uncertain. In general, the positive effects of elevated CO_2 on plant–water relations are expected to be offset by increased evaporative demand under warmer temperatures (IPCC, 2007b); therefore the impact of elevated CO_2 on water demand is usually not considered in studies of agricultural water management under climate change.

Higher water temperatures and projected changes in water extremes, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution such as sediments, nutrients and dissolved organic carbon, with possible negative impacts on agricultural production, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover and soil management practices (IPCC, 2014). Mullan and Barrett-Lennard (2010) suggested that climate change is expected to reduce water availability in general, making the use of low quality water resources more common.

In low-lying coastal areas, sea-level rise is projected to increase flooding depth, resulting in shorter duration for crops, and to extend salinity intrusion into the surface and groundwater systems in estuaries, causing a decrease of freshwater availability for agricultural production. Without adaptation, it is projected that hundreds of millions of people will be affected by coastal flooding and displaced due to land loss by the year 2100; the majority of those affected are from East, South-east and South Asia. Protecting against flooding and erosion is considered economically rational for most developed coastlines in many countries under all socio-economic and sea-level rise scenarios analysed (IPCC, 2014).

Locally, irrigated agriculture may face new problems linked to the spatial and temporal distribution of streamflow. For instance, at low latitudes, especially in South-east Asia, early snowmelt may cause spring flooding and lead to a summer irrigation water shortage (IPCC, 2007b). In most dry subtropical regions, climate change is projected to reduce renewable surface water and groundwater resources significantly. This will intensify competition for water among agriculture and other sectors, and affect regional water supply, energy generation and food security. In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. The effects on water resources and irrigation requirements of changes in vegetation due to increasing GHG concentrations and climate change remain uncertain (IPCC, 2014). There is high confidence that irrigation demand will increase significantly in many areas (by more than 40% across Europe, USA and parts of Asia). Other regions – including major irrigated areas in India, Pakistan, and south-eastern China – might experience a slight decrease in irrigation demand, due for example to higher precipitation, but only under some climate change scenarios.

However, region-to-region variations in different studies were very heterogeneous. For example, using seven global hydrological models with a limited set of projections, Wada *et al*. (2013) estimated a global increase in irrigation demand by the 2080s (ensemble average 7–21% depending on emissions scenario). By contrast, based on projections from two general circulation models (GCMs) and two emissions scenarios, Zhang and Cai (2013) suggested a slight global decrease in crop water deficits in both irrigated and rainfed areas by the 2080s, which can be explained partly by a smaller difference between daily maximum and minimum temperatures.

With the changes in temperature and precipitation under climate change, shifting of crops from present locations to new locations will occur as one option in adaptation to climate change. In a study assessing the impact of climate change on agricultural land for 16 crops by comparing the global spread of farmland between the 'current' period (1981–2010) and a future period (2071–2100), Zabel *et al*. (2014) calculate a potential global net increase in land climatically suitable for crops of 4.7 million km^2, from 54.2 million km^2 to 58.9 million km^2. These figures include land that is both rainfed and irrigated, and exclude protected areas and dense forest because of the importance of conserving these to protect ecosystem services, such as carbon storage. However, the authors emphasize a downward shift in land quality: 3.9 million km^2 is projected to be 'highly suitable' for crops, compared with 4.6 million km^2 for the current period. In turn, more land will be classified as 'marginally suitable' or 'moderately suitable', with increases of 3.8 million km^2 and 1.6 million km^2, respectively, under these categories. In this study, irrigation areas are assumed not to change, but in practice, it is likely that irrigation systems will be expanded to the areas highly suitable for crops in terms of soil, terrain and climate.

IPCC (2007a, 2014) warn that increased demand for irrigation, from both surface and groundwater sources, will result both from changed climatic conditions and from increased demand for food by a growing population. Globally, the impacts of climate change on increasing irrigation water requirements could be nearly as large as the changes projected from socio-economic development in this century (Turral *et al*., 2011). Agricultural production systems and water resources will be critically shaped in the coming decades by the interaction of climate with non-climatic drivers: demographic, socio-economic, technological and lifestyle changes.

IPCC (2013) stress that current water management practices may not be robust enough to cope with the impacts of climate change on agriculture and other water use sectors. Adaptive water management techniques, from field-scale water-saving techniques, to basin-level scenario planning, learning-based approaches, and flexible and low-regret management solutions, can help create resilience to uncertain hydrological changes and impacts due to climate change. Much of the adaptation cost in water management will be needed in developing countries, which face barriers including lack of human and institutional capacity, financial resources, awareness and communication.

1.2 Global Assessment on Agricultural Water Management

Maskey *et al*. (Chapter 2, this volume) review the global literature on impacts of climate change on agriculture and prospects for adaptation. They find that sensitivity of agriculture to climate change varies across the globe, and in general, developing countries, where more than 800 million people are already undernourished, will be hardest hit. There has been considerable progress in approaches for assessing the impact of climate change on agriculture and irrigation and in evaluation of adaptation measures, but critical challenges and constraints associated with climate change impact and adaptation remain. Limited understanding of the interactions between, and relative importance of, factors like elevated ozone and CO_2 levels, extreme weather conditions, weed variety, socio-economic changes and adaptation responses mean that diverse adaptation options from farm to policy level are essential. Most published studies on adaption focus on modification of existing management practices to improve crop yield, using process-based models, but do not account for trade-offs between crop production and resource availability, which influence the farmer's decision-making and profitability. The authors propose that more effort is required to incorporate social, financial, institutional and technical constraints and the limitations of resources and adaptive capacity into adaptation frameworks and planning.

Sood (Chapter 3, this volume) warns that, with world population increasing to about 9 billion and the per capita GDP rising, the future demand for water for domestic and industrial sectors will compete with the agricultural water demand. Results from a water accounting and global food trade model, the Water, Agriculture, Technology, Environmental and Resource Simulation Model (WATERSIM), indicate that the proportion of consumptive water demand for agriculture will decrease from around 72% of the total demand in 2010, to 37% in case of business-as-usual, 27% in case of an optimistic socio-economic scenario and 50% in case of a pessimistic socio-economic scenario. The greatest increase in demand for consumptive water comes from domestic and industrial sectors, although to maintain optimum yields, around 16–19% more irrigation water will be required on average due to higher evaporative demand. Sood concludes that with improved agricultural water management and liberalized global food trade, there are enough resources globally not only to meet the future demand but also to reduce malnutrition.

1.3 Crop Water Requirements under Climate Change

Analysing past climate data is one way to assess potential impacts of climate factors on crop water requirement. Liu *et al*. (Chapter 4, this volume) evaluate the effects of climate in the Huang-Huai-Hai Plain (3H Plain) in the northern China using observed climate data for the period 1981–2009 to estimate reference evapotranspiration (ET_0), then analyse the sensitivity of crop water requirement (ET_c) of major climatic variables and regional responses of precipitation deficit in different crop growth stages. The results show that temperature was the most sensitive variable in general for the 3H Plain, followed by solar radiation, wind speed and relativity humidity. Relative humidity was the factor most closely correlated with precipitation deficit.

Working in the same region in China, where water is scarce and climate change is likely to exacerbate water stress, Xia *et al*. (Chapter 5, this volume) explore regional crop responses to climate change, using the wheat–maize double-cropping system as an example. Their results indicate that under likely climate change scenarios, production of winter wheat will increase (with slightly intensified evapotranspiration), but in contrast, summer maize production will slightly decline (with a significant increase of evapotranspiration). The results also indicate that wheat is more resilient to climate change than maize. To mitigate the impacts of climate change on agricultural water use, they propose a range of agricultural water management measures and policies, including improving the performance of participatory irrigation management reform, establishing a water rights system, reforming agricultural water price, and promoting the adoption of agricultural water-saving technology.

Lansigan and Dela Cruz (Chapter 6, this volume) also report local observational evidence of changing climate based on available historical weather data sets in the Philippines. The authors select plausible climate scenarios and downscaled climate projections, both dynamic and statistical, for analysing crop yields using a calibrated crop simulation model for a standard rice variety (IR-64) and a local maize variety (IPB-911). Their results indicate a reduction from 8 to 14% in crop yields for every 1°C temperature increase depending on season and location. For adaptation strategies in agricultural water management, the authors propose location-specific measures based on best practices including adjusting the planting calendar, improving water use efficiency and irrigation water management, water impoundment, planting stress-tolerant varieties, and weather index-based insurance for crop production.

Since the agriculture sector is highly vulnerable to climate change in many parts of the world, there is an increasing concern among farmers, researchers and policy makers about the potential impacts of climate change on food security and livelihoods. Kakumanu *et al*. (Chapter 7, this volume) review the current state of understanding of climate change impacts on irrigation water in South Asia and specifically on the crop yield and relevant adaptation measures in three major river basins, the Godavari, Krishna and Cauvery in India. An optimization model was used to evaluate the different adaptation practices and their potential to maximize rice production and income, and minimize water use for the mid- and end-century climate change scenarios. The authors conclude that adaptation practices at farm level, such as system of rice intensification, machine transplantation, alternate wetting and drying and direct seeding, could reduce the water and labour use by 10–15% and stabilize rice production in the long term. They suggest that to adapt to the impacts of climate change on agricultural water management, technology upscaling is an alternative but should be backed up with well-planned capacity-building programmes for farmers.

1.4 Agricultural Water Management under Sea-level Rise

The Mekong River Delta is one of the regions most seriously impacted by sea-level rise (World Bank, 2007), which will aggravate inundation and salinity intrusion and hence strongly influence agricultural production. Phong *et al*. (Chapter 8, this volume) focus on the impacts of sea-level rise in Bac Lieu province, a low-lying coastal province in the Mekong River Delta of Vietnam. The province receives fresh water from the Mekong mainstream on the east side, and dyke and sluices for protection from salinity intrusion were built at the south-west. The authors use a hydraulic and salinity model for simulating water level, flow and salinity in the canal network for years of low, average and high water volume from upstream, and different levels of projected sea-level rise from 12 to 75 cm. Their results indicate that flooding depth increases directly with sea-level rise but that for sea-level rise less than 30 cm, salinity slightly decreases, due to increasing freshwater inflows from the mainstream. This contradicts many previous studies, which generally conclude that the area of salinity intrusion is always larger under sea-level rise. However, when sea-level rise is higher than 30 cm, saline water intrudes into the mainstream and freshwater intake canals, and additional structures (dykes and sluices) will be needed for salinity control.

Most of the Mekong Delta's aquaculture production occurs in the floodplains and coastal areas that are highly exposed and vulnerable to climate change impacts and sea-level rise. Adaptation in water management for cropping systems, such as upgrading dykes to reduce flooding and salinity intrusion, will benefit other production systems, particularly aquaculture. Kam *et al.* (Chapter 9, this volume) present an example of economic evaluation of autonomous adaptation by shrimp and catfish farms in the Mekong Delta of Vietnam. The study shows that planned adaptation measures can help defray catfish farmers' escalating costs of raising pond dykes in response to increased flooding in the delta, if government policy and public investment in adaptation to climate change, particularly for water management, take account of socio-economic development targets of the aquaculture industry. Because of the high level of uncertainty surrounding commodity prices and changes in production technologies, a 'no-regrets' strategy of reducing the high dependence on shrimp and catfish culture and diversifying into more ecologically oriented production systems is recommended, to hedge the aquaculture industry against the increasing risks and uncertainties brought about by climate change.

1.5 Adaptive Agricultural Water Management

Groundwater resources have been exploited in many regions to respond to the increase in water demand for agriculture under climate variability and climate change. Villholth (Chapter 10, this volume) considers groundwater resources in transboundary aquifers as significant water reserves for sustainable agricultural and socio-economic development in the context of Africa, Asia, the Middle East and Latin America. The author highlights that integrated surface and groundwater measures are important for local, smaller-scale, no-regrets adaptation, as well as for larger-scale, strategic adaptation. Socio-economic and institutional aspects, encompassing international law and specific adapted international agreements as well as bottom-up participatory processes, are critical for attaining success on the ground.

Although climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions (IPCC, 2007b), adaptation to climate change is still based on past experiences. An approach in adaptation is to compare future water demand with lessons from similar conditions in the past, to select possible alternatives. In an example of this approach, Savoskul and Shevnina (Chapter 11, this volume) model the future inflow to the irrigation scheme of the Syr Darya Basin in Central Asia under two climate scenarios based on IPCC core models. Simulating water allocation in the basin in 2070–2099 shows that 14–21% of water demands in the agriculture sector in a normal hydrological year and 28–51% in a dry year are likely to be unmet. The challenges expected from future climate change can be paralleled to those resulting from the political change due to the collapse of the USSR, which left 18% (normal year) and 46% (dry year) of agricultural water demands unmet in 1992–2001. Therefore the authors suggest that the adaptation measures employed in the post-Soviet transitional period can serve as a basis for future climate change adaptation strategies.

Water-saving techniques in agriculture are considered as potential measures to adapt to climate change impacts. These techniques do not only improve water use efficiency but can also contribute to mitigation of long-term climate change. The effects of mitigation on irrigation water requirements could be significant in the coming decades, with large overall water savings, both globally and regionally, although Turral *et al.* (2011) suggest that production in some regions could initially be negatively affected by mitigation actions. Flooded rice fields are a large anthropogenic source of the greenhouse gas (GHG) methane (CH_4). Aeration of the paddy field can reduce methane emissions and at the same time save water. Sander *et al.* (Chapter 12, this volume) analyse the effects of different water-saving techniques such as alternate wetting and drying (AWD) on revenues of rice farmers and climate-change mitigation in the Philippines. Results from field experiments show that methane emissions can be reduced by an average of 37% with a single drainage and by 43% with multiple aerations; nitrous oxide emissions increase but not sufficiently to offset the reduction in CH_4 emissions. To improve uptake, the authors propose initial promotion of a simple, single midseason drainage that only requires water control during approximately 1 week. Uptake is highly dependent on provision of incentives for farmers, which could be coordinated through the Clean Development Mechanism. Other indirect benefits from AWD, such as less crop lodging, reduced pest damage and better soil conditions, need to be scientifically validated.

Policy settings for adaptation to climate change have to deal with the uncertainty inherent in projections. Prosinger *et al.* (Chapter 13, this volume) link the dominant approach of uncertainty presented in the climate-change discourse with policy discussions on climate adaptation strategies in Lao PDR as a case study. While the different perceptions and interpretations of climate-change uncertainty by different policy makers might lead to multiple problem framings, they also reflect structural impediments and institutional barriers in the overall formulation process of climate-change policy and adaptation strategies. The authors emphasize that understanding of these different notions of uncertainty is crucial to increase the actual significance of climate change policy, in particular for sectors that are strongly affected by climate change such as agriculture and water management, and that policy and governance responses to climate change need to be formulated based on a more nuanced, sophisticated understanding of how various policy actors and stakeholders perceive and experience uncertainty.

1.6 Uncertainty and Knowledge Gaps

Despite significant efforts in quantifying future changes in hydrological variables and their impacts on agricultural water management, responses to climate change are limited by uncertainty at all stages of the assessment process. Uncertainty derives from the range of socio-economic development scenarios, the range of climate model projections for a given scenario, the downscaling of climate effects to local/regional scales, impact assessments, and feedbacks from adaptation and mitigation activities (Bates *et al.*, 2008). Approaches and tools are needed to facilitate the appraisal of adaptation and mitigation options across multiple water-dependent sectors (IPCC, 2007b).

A number of key gaps in information and knowledge for agricultural water management, particular in developing countries, is indicated in the studies in this book and other reports (IPCC, 2007b, 2014; Bates *et al.*, 2008):

- Records of climate parameters such as solar radiation, relative humidity and wind speed, and of hydrological parameters such as flow and water quality, including sediment, in river and irrigation systems are often very short, and available for only a few regions.
- Knowledge is lacking on plant evapotranspiration responses to the combined effects of rising atmospheric CO_2, rising temperature and rising atmospheric water vapour concentration, as well as soil moisture changes due to reduction in surface water availability.
- Uncertainty in modelling climate variability, in particular precipitation, remains high. Projections vary widely between models, in particular when downscaling from large-scale climatic models to catchment. The approaches of ensemble of climate projections using climate models and observational constraints (Stott and Forest, 2007) or probabilistic approaches (Frieler *et al.*, 2012) do not assure removal of uncertainty.
- Feedbacks between land use and climate change (including vegetation change and anthropogenic activity such as irrigation and reservoir construction) have not been analysed extensively, in particular if impacts on local climate are considered.
- Information on groundwater is lacking in many regions.

- Climate-change impacts on water quality are still poorly understood; so far only salinity impacts have been studied in any detail.

1.7 Building Resilience Through Agricultural Water Management

Nicol and Kaur (2009) emphasize that adaptation options designed to ensure water supply require integrated demand-side as well as supply-side strategies. Demand management, which aims to regulate withdrawals at sustainable levels through such measures as the promotion of sustainable use, pricing mechanisms and water-saving techniques, will become increasingly important in areas where relative scarcity and competition between water-dependent sectors is increasing. Supply management, through increased storage capacity, abstraction from water course, rainwater harvesting and recharge activities and/or introducing incentives for water conservation, will become a priority where inter-annual resource availability is likely to change significantly. One novel and promising alternative to deal with extreme events under climate change is the harvesting of floods for later use in agriculture by underground taming of floods (Pavelic *et al.*, 2012; Smakhtin *et al.*, 2014).

Over the last decade, the International Water Management Institute has formulated strategies to help communities in developing countries to reduce risks and build resilience through better water management (see, for example Comprehensive Assessment of Water Management in Agriculture, 2007; Johnston *et al.*, 2010; Giordano *et al.*, 2012; McCornick *et al.*, 2013):

- Think more creatively about water storage to overcome short and long-term dry spells, employing a range of approaches along the storage continuum, from small ponds to large reservoirs, groundwater recharge, water harvesting and soil-water conservation.
- Tailor water management strategies to meet changing local needs, as climate change drives new cropping and land-use patterns, ensuring that water resources are developed and managed fairly so that vulnerable groups are not disproportionately burdened by the impacts of variability.
- Increase water productivity through higher yields, crop diversification, and integrating livestock and fisheries. At the global scale, improved productivity helps reduce GHG emissions by curbing the need to convert land for agricultural purposes.
- Improve basin water management and allocation to deal with increased variability in flows, by engaging social and institutional governance mechanisms, as well as technical approaches.
- A shift from ‘drought response’ to ‘drought risk mitigation’, with new approaches to early warning and insurance to prepare farmers for climate variability.
- Use our understanding of existing climate variability as the basis for dealing with future change, and improve understanding of the impacts of climate change on variability.
- Improve the understanding of the role of natural ecosystems in buffering variability.

Adapting water management to climatic variability cannot be done in isolation, but is best addressed in the context of sustainable development. Improving water management to deal with climate variability can help vulnerable rural communities to build resilience, diversify their livelihoods and reduce risk. Building resilience now will bring benefits regardless of how and when climate change plays out on the ground (McCornick *et al.*, 2013).

References

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P. (eds) (2008) *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, Switzerland, 210 pp.

Bruinsma, J. (2003) *World Agriculture: Towards 2015/2030. An FAO Perspective*. Earthscan, London, 444 pp.

Comprehensive Assessment of Water Management in Agriculture (2007) *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, and International Water Management Institute (IWMI), Colombo, Sri Lanka, 643 pp.

Frieler, K., Meinshausen, M., Mengel, M., Braun, N. and Hare, W. (2012) A scaling approach to probabilistic assessment of regional climate change. *Journal of Climate* 25(9), 3117–3144.

Giordano, M., de Fraiture, C., Weight, E. and van der Bliek, J. (eds) (2012) *Water for Wealth and Food Security: Supporting Farmer-Driven Investments in Agricultural Water Management*. Synthesis Report of the AgWater Solutions Project, International Water Management Institute (IWMI), Colombo, Sri Lanka, 48 pp.

IPCC (2007a) Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team, Pachauri, R.K and Reisinger, A. (eds)). IPCC, Geneva, Switzerland, 104 pp.

IPCC (2007b) Climate Change 2007: Impacts, Adaptation and Vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (eds) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 976 pp.

IPCC (2013) Climate Change 2013: The Physical Science Basis. In: 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) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, 1535 pp.

IPCC (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. In: 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., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds) Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, 1132 pp.

Johnston, R., Lacombe, G., Hoanh, C.T., Noble, A., Pavelic, P., Smakhtin, V., Suhardiman, D., Kam, S.P. and Choo, P.S. (2010) *Climate Change, Water and Agriculture in the Greater Mekong Subregion*. IWMI Research Report 136. International Water Management Institute (IWMI), Colombo, Sri Lanka, 60 pp.

McCornick, P., Smakhtin, V., Bharati, L., Johnston, R., McCartney, M., Sugden, F., Clement, F. and McIntyre, B. (2013) *Tackling Change: Future-Proofing Water, Agriculture, and Food Security in an Era of Climate Uncertainty*. International Water Management Institute (IWMI), Colombo, Sri Lanka, 36 pp.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Mullan, D.J. and Barrett-Lennard, E.G. (2010) Breeding crops for tolerance to salinity, waterlogging and inundation. In: Reynolds, M.P. (ed.) *Climate Change and Crop Production*. CABI Series in Climate Change. CAB International, Wallingford, UK.

Nicol, A. and Kaur, N. (2009) *Adapting to Climate Change in the Water Sector*. Background Note. Overseas Development Institute, London.

Pavelic, P., Srisuk, K., Saraphirom, P., Nadee, S., Pholkern, K., Chusanathas, S., Munyou, S., Tangsutthinon, T., Intarasut, T. and Smakhtin, V. (2012) Balancing-out floods and droughts: opportunities to utilize floodwater harvesting and groundwater storage for agricultural development in Thailand. *Journal of Hydrology* 470–471, 55–64.

Smakhtin, V., Pavelic, P., Amarnath, G. and McCartney, M. (2014) Managing water variability, from floods to droughts. In: van der Bliek, J., McCornick, M. and Clarke, J. (eds) *On Target for People and Planet: Setting and Achieving Water-Related Sustainable Development Goals*. International Water Management Institute (IWMI), Colombo, Sri Lanka, 52 pp.

Stott, P.A. and Forest, C.E. (2007) Ensemble climate predictions using climate models and observational constraints. *Philosophical Transactions of the Royal Society A – Mathematical, Physical and Engineering Sciences* 365, 2029–2052.

Turral, H., Burke, J. and Faures, J.-M. (2011) *Climate Change, Water and Food Security FAO Water Report 36*. Food and Agriculture Organization for the United Nations (FAO), Rome.

UN Water (2009) *Water in a Changing World*. The United Nations World Water Development Report 3. UN Water, Geneva, Switzerland.

Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F.T., Stacke, T., Tessler, Z. and

Schewe, J. (2013) Multi-model projections and uncertainties of irrigation water demand under climate change. *Geophysical Research Letters* 40(17), 4626–4632.

World Bank (2007) *The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis*. World Bank Policy Research Working Paper (WPS4136), February 2007. The World Bank Group, Washington, DC.

Zabel, F., Putzenlechner, B. and Mauser, W. (2014) Global agricultural land resources – a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. *PLoS ONE* 9(9), e107522. DOI: 10.1371/journal.pone.0107522.

Zhang, X. and Cai, X. (2013) Climate change impacts on global agricultural water deficit. *Geophysical Research Letters* 40(6), 1111–1117.