THE MEKONG'S FUTURE FLOWS

Quantifying hydrological changes and developing adaptation options

Long Phi Hoang

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Quantifying hydrological changes and developing adaptation options

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Abstract

This multidisciplinary study focuses on projecting and adapting to future hydrological changes in the Mekong – an international river of global significance in terms of rapidly increasing human pressures and climate-change vulnerability. A modelling framework was developed to project future changes in both the river flow regime and hydrological extremes (i.e. high/low flows and floods), under multiple scenarios of climate change, irrigation and hydropower developments. Furthermore, we developed a combined quantitative-qualitative approach to develop suitable adaptation measures and strategies to future floods in the Mekong Delta being a key vulnerability hotspot.

Results show that the Mekong's future flow regime is subjected to substantial changes under climate change and human developments. Climate change will intensify the hydrological cycle, resulting in increasing average river flows (between +5 % and +16%, annually), and more frequent and extreme high flows during the wet season. Flow regime shows substantial alterations in the seasonal flow distributions under the combined impacts of climate change, irrigation expansions and hydropower developments. While dry season flows increase strongly (monthly changes up to +150%), wet season flows show contrasting changes with reductions during June - October (up to -25%) and substantial increases during November – December (up to 36%). A follow-up modelling assessment for the Mekong Delta shows substantial increases in flood hazards under climate change and sea level rise, shown by higher flood frequencies and flood depths across the whole delta. Increasing flood hazards therefore represents a key issue to be addressed in terms of future adaptation. The adaptation appraisal study further shows that effective adaptation requires looking beyond sole infrastructural investments. Instead, technological innovations for flood risk management combined with improved governance and institutional capacities offer ample opportunities to adapt to future hydrological changes.

This study projects substantial future hydrological changes under future climate change and accelerating socioeconomic developments and shows potentially serious consequences for water related safety and sustainable water resources uses and allocations. Furthermore, this study demonstrates amble opportunities to manage future changes through strategic development planning and through adaptive interventions. Insights from this study address the needs for quantified future hydrological changes and emphasize adequate adaptation to the associated risks in an important international river experiencing climate change and rapid socioeconomic developments.

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CHAPTER 1

Introduction

1.1. Background and problem outline

The Mekong – largest river in Southeast Asia, is a transboundary river of global significance in terms of climate-change vulnerability and rapidly increasing human pressures on water resources. The river flows across six countries (i.e. China, Myanmar, Laos, Thailand, Cambodia and Vietnam) and provides essential resources for about 70 million people and the national economies along its watercourse (MRC, 2005; Ziv et al. 2012). Many economic sectors in the region are strongly dependent on the Mekong's flows and water resources, especially agriculture, fisheries and hydropower production (Ziv et al. 2012). However, recently accelerating economic developments and population growth also represent important environmental stressors due to their potential implications for sustainable water resource uses and allocations (MRC, 2011a). Additionally, the Mekong River also constitutes a major source of water-related risks, especially in views of future climate change. Hydrological extremes including floods and droughts frequently affect human safety, livelihoods and economic developments (MRC, 2005; Delgado et al. 2012). These extreme events are expected to increase under climate change, representing one of the most important risk factors in the region in the coming decades (Eastham et al. 2008; Västilä et al. 2010; Global Risks Report, 2016).

Climate change is expected to cause substantial hydrological changes including changes in the river's flow regimes and hydrological extremes in the Mekong basin. Recent studies have shown impacts of climate change on both the annual and seasonal river flows, consequently affecting water resources and safety risks (Eastham et al. 2008; Västilä et al. 2010; Lauri et al. 2012). Direct impacts of climate-change-induced hydrological changes include more extreme and frequent floods, and to a lesser extent, droughts (Eastham et al. 2008; Västilä et al. 2010). The Vietnamese Mekong Delta, with average elevation of just a few meters above sea level, represents a highly vulnerable region across the basin (Adger, 1999; Wassmann et al. 2004; Smajgl et al. 2015). The delta has long been identified as one of the global top-3 most vulnerable river deltas to climate change impacts and sea level rise (Ericson et al. 2006).

In addition, population growth and economic development activities in the Mekong region are accelerating rapidly, resulting in increasing pressures on water resources. Food and energy production in the basin are growing rapidly as results of growing domestic demands and the region's stronger integration into the global market (MRC, 2011a).

Increasing flood production is largely powered by agricultural land expansions, which mainly rely on surface water irrigation from rivers. According to MRC (2011a), irrigated crop area can increase up to two times, reaching 8.4 million hectares within the coming three decades. Similarly, energy sector has been experiencing steady growing trends, with a strong focus on hydropower as the most attractive energy source (Grumbine and Xu, 2011; Lauri et al. 2012). Although the Mekong remains one of the world's last undammed major rivers, several countries including China, Laos and Vietnam have recently set major hydropower development plans in motion (Grumbine et al, 2012; Ziv et al. 2012). Future socioeconomic developments including irrigated land expansions and hydropower developments will likely affect the river's flow regime (Lauri et al. 2012), water resources (Piman et al. 2013) and aquatic ecosystems (Arias et al. 2014). All in all, future socioeconomic developments and climate change are expected to have substantial hydrological impacts, which in their turns cause critical challenges for sustainable development in the Mekong region. In this context, proper quantifications and effective adaptation to future hydrological changes are highly important for maintaining water related safety and sustainable water resources in the Mekong basin.

Knowledge gaps and research focus

Despite stronger research focus and an increasing number of recent studies, two important knowledge gaps about future hydrological changes in the Mekong basin exist. The first knowledge gap relates to characterizing and quantifying future hydrological changes under both climate change and accelerating socioeconomic development activities. Current flow projections for the Mekong remain highly uncertain, mainly due to prevalent uncertainties in existing climate change projections (Kingston et al. 2011; Thompson et al. 2013). As a result, current studies mostly focus on changes in the monthly and seasonal averages while paying little attention to hydrological extremes, which require analyses at shorter (e.g. daily) timescale. Currently, quantifications of future changes in hydrological extremes including high flows, low flows and floods are very limited for the Mekong, although such information is especially relevant for water management and adaptation decision making (Campbell, 2007; Kiem et al. 2008). Additionally, while river flows are likely driven by both climate change and socioeconomic developments including irrigation expansions and hydropower developments (Keskinen et al. 2010; Lauri et al. 2012), few studies integrate multiple driving factors in future projections. As a result, the question of how the Mekong's the future flows are affected by the combined impacts of multiple driving factors remains largely open.

The second knowledge gap relates to adaptation to future hydrological changes. Anticipatory adaptation to the changing flow dynamics and increasing risks including floods and droughts proves highly challenging due to poor development and evaluations of effective measures and strategies (Keskinen et al. 2010; Bastakoti et al. 2014). In many vulnerable regions across the basin including the Mekong Delta, policies and intervention strategies for adaptation are largely under developed, leading to difficulties in implementation (Lebel et al. 2010; SIWRP, 2012; MDP, 2013). Consequently, water-related safety and economic activities are increasingly affected by hydrological changes across the basin. Against this background, this study focuses on quantifying future hydrological changes in the Mekong River basin and subsequently developing intervention strategies to reduce and adapt to the associated risks.

1.2. Research objective and questions

The main objective of this thesis is two-fold:

1. *To quantify future hydrological changes (both flow regimes and hydrological extremes) in the Mekong basin; and*
2. *To develop measures and strategies to adapt to the projected hydrological changes.*

The research objective was achieved through a stepwise procedure, using a multidisciplinary methodological framework, where I combined quantitative and qualitative methods. First, I set up a distributed hydrological model i.e. the VMod (Lauri et al. 2006) for the Mekong basin to assess future changes in the future flow regime and hydrological extremes, including a relatively large ensemble of downscaled and bias corrected climate change scenarios. Second, I implemented an integrated impacts assessment to characterize and quantify future flow changes caused by multiple driving factors, namely climate change, irrigated land expansion, and hydropower dam developments. In the third step, I zoomed in on the Mekong Delta – the vulnerability hotspot to hydrological changes, and further assessed changes in the future flood hazards, which are expected to increase based on findings from the first step. Here I developed a model chain to provide probabilistic and spatially explicit estimates of the extreme flood hazards, taking into account both upstream inflow changes and sea level rise. In the last step, I developed a multidisciplinary approach for appraising measures and strategies to adapt to future flood risks in the Mekong Delta. Four corresponding research questions were formulated:

Question 1: *What are the impacts of future climate change on the Mekong's flow regime and hydrological extremes?* (Chapter 2)

Question 2: *How will the Mekong's flow regime change under the combined impacts of multiple driving factors including climate change, irrigated land expansion and hydropower developments?* (Chapter 3)

Question 3: *How will upstream climate change induced hydrological changes and downstream sea level rise affect flood hazards in the Mekong Delta?* (Chapter 4)

Question 4: *What are the suitable measures and strategies for the Mekong Delta to adapt to future flood risks?* (Chapter 5)

1.3. Methodology

This study addresses the research objectives and research questions using a combined quantitative-qualitative methodological framework (Figure 1.1). Research questions 1 to 3 concern future changes in the Mekong River's flows and floods under the influences of multiple driving factors, including climate change, irrigation expansions and hydropower developments. These questions were addressed through a series of scenario assessments using modelling tools. Findings from these questions provide necessary boundary conditions for the following step (i.e. question 4 - adaptation) by identifying focal impacts (i.e. increasing floods) and vulnerability hotspot region (i.e. the Mekong Delta). Research question 4 was then addressed through a novel approach where qualitative methods (surveys and content analyses) were combined with statistical inferences to develop strategies and measures for adaptation to future hydrological changes focusing on flood risks. Figure 1.2 provides further technical details about the main research tools and their interlinkages in this study.

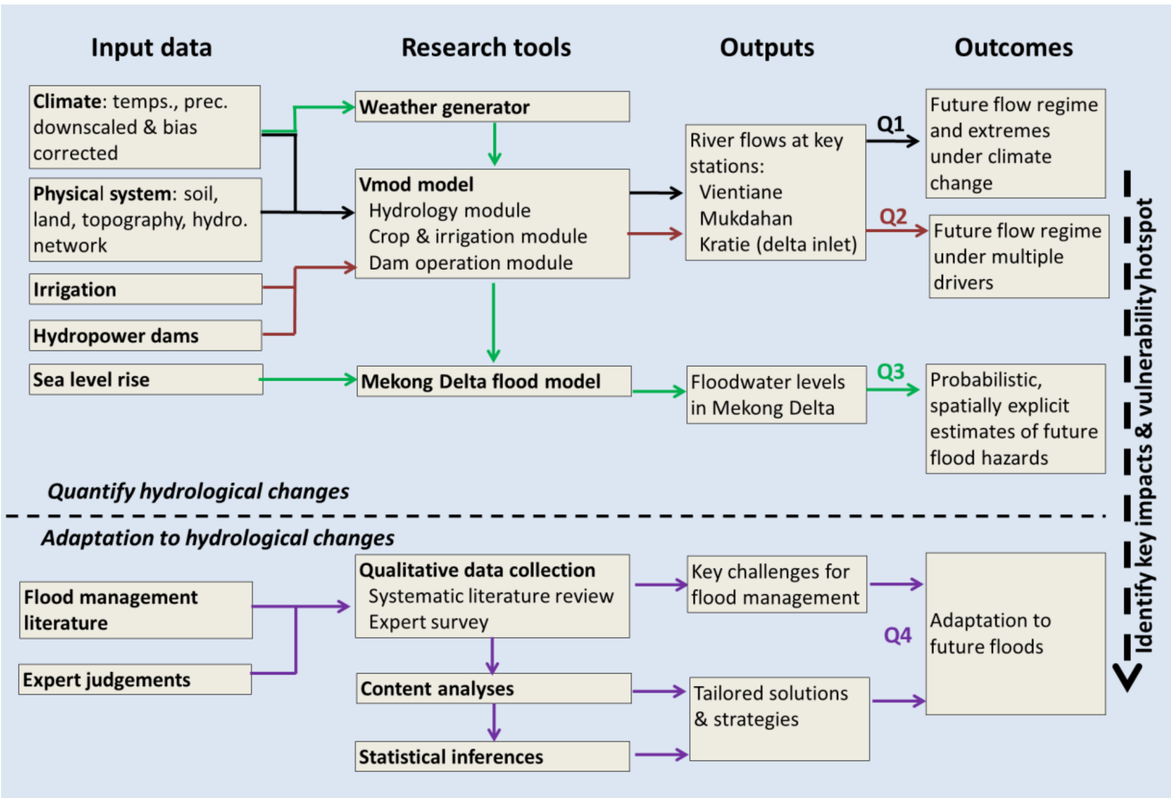

Figure 1.1 The study's methodological framework

Hydrological modelling to assess future hydrological changes

Hydrological modelling in this study covers both basin-wide processes (i.e. rainfall-runoff and anthropogenic activities) as well as sub-basin flood dynamics (i.e. the Mekong Delta). The core of the modelling framework is the VMod – a state-of-the-art distributed hydrological model (Lauri et al. 2006). VMod's simulation capabilities ranging from rainfall-runoff modelling to simulating human modifications to river flows make this model highly suitable for this study. In this study, the VMod model was further developed to integrate three dynamically-linked modules, namely the hydrological module for simulating rainfall-runoff; the newly developed crop and irrigation module for simulating crop growth and irrigation; and the dam operation module for simulating river flows under dams operations (Figure 1.2). Dynamic linkages between the modules allow for simultaneous simulations of river flows as results of direct interactions between multiple driving factors such as rainfall, evaporation, crop water use and irrigations, and flow regulations caused by dam operations. Comparing to other existing hydrological models for the Mekong basin (see, for example, a model inventory by Johnston & Kummu, 2012), the VMod also features relatively higher spatial resolution (i.e. 5 km x 5 km), allowing for proper simulations of irrigated land expansions and the resulted impacts on river flows.

Additionally, in this study I also linked VMod with a weather generator and a flood simulation model to investigate flood hazards in the downstream Mekong Delta, focusing on extreme events as results of both climate-change-induced inflow changes and sea level rise. The weather generator (Buishand and Brandsma, 2001; Leander et al. 2005), which uses nearest neighbours resampling method, was used to create long-term (1000-year) synthetic climate data for VMod simulations. The Mekong Delta flood model (Dung et al. 2011) is a 1-dimensional hydrodynamic model for simulating flows and water levels in the modelled floodplains. This hydrodynamic model was subjected to a multiobjective auto-calibration (i.e. optimising for both flood depths and flood extents), showing good simulation performance for the Mekong Delta (Dung et al. 2011). Together, the VMod model, the weather generator and the flood model represent a model chain capable of providing spatially explicit and probabilistic estimates of extreme floods in the Mekong Delta.

Multidisciplinary approach for adaptation appraisal

To appraise adaptation to future floods, multiple adaptive measures and strategies were developed using a novel approach which combines expert surveys, content analysis, and statistical inferences. The study first used online surveys to collect data from relevant experts about potential measures for managing flood risks in views of the future climate change impacts and socioeconomic developments. Collected data in text datatype were then standardized and structured using open-coding technique to identify potential measures. Next, thematic grouping was used to combine these measures into different adaptation strategies. Along these two steps, several statistics were calculated to determine the occurrence frequencies and correlations between the measures, strategies and flood management aspects. The developed methodological approach yielded a comprehensive set of adaptation options and strategies, and furthermore provided important insights about how to tailor these options and strategies to specific flood management challenges.

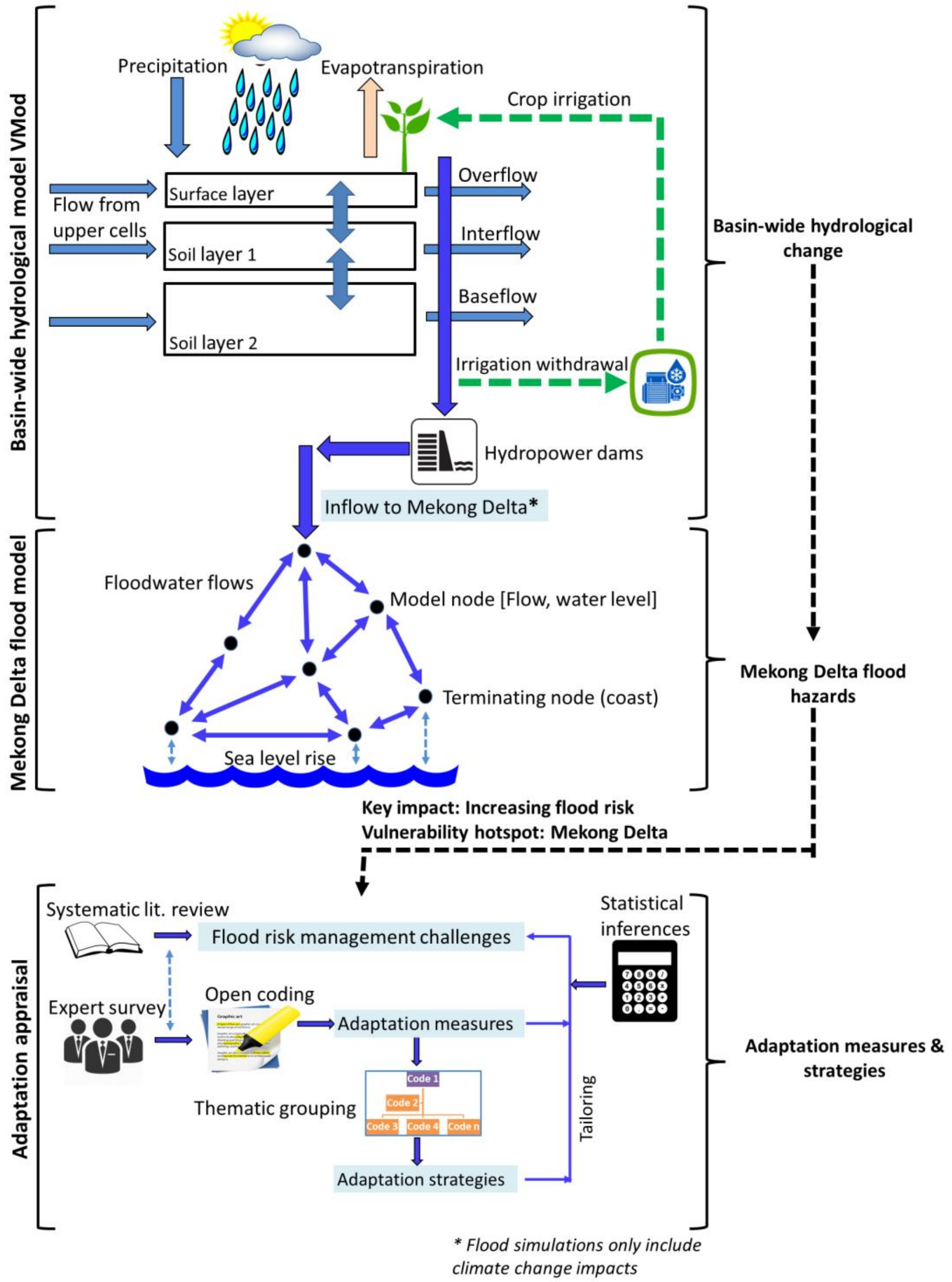

Figure 1.2 Schematic representations of main research tools and their interlinkages. The VMod model's scheme was further modified based on Lauri et al. (2006)

1.4. The Mekong River basin

The Mekong River in Southeast Asia represents a special case of a large river system with multiple unique features. The river has a total length of 4 800 km and a basin area of 795 000 km^2 (Figure 1.3). Despite this relatively moderate area (world ranking 21st), the Mekong exhibits an exceptionally high flow volume per unit area in comparison to other major rivers of the world. With an annual flow volume of 475 km^3, the Mekong is the 10th largest river in this regard (Dai and Trenberth, 2002). The river's flow dynamics are still relatively natural since the Mekong remains one of the last major rivers that are largely undammed (Grumbine and Xu, 2011). This natural flow regime greatly supports the world's 2nd most biodiverse aquatic ecosystem after the Amazon River, highlighted by the Tonle Sap Lake in Cambodia (Ziv et al. 2012). The Tonle Sap itself also represents the only freshwater lake on Earth with a seasonal flow reversal mechanism[1]. The Mekong Delta is one of the world's largest and most populous, yet highly vulnerable river deltas to climate change impacts and sea level rise (Adger, 1999; Ericson et al. 2006). The river's cross-boundary flows and its crucial roles for livelihood provisions, economic growth and ecosystem dynamics highlight a particularly high-stake river in terms of regional developments and geopolitics (Lebel et al. 2005; Keskinen et al. 2010).

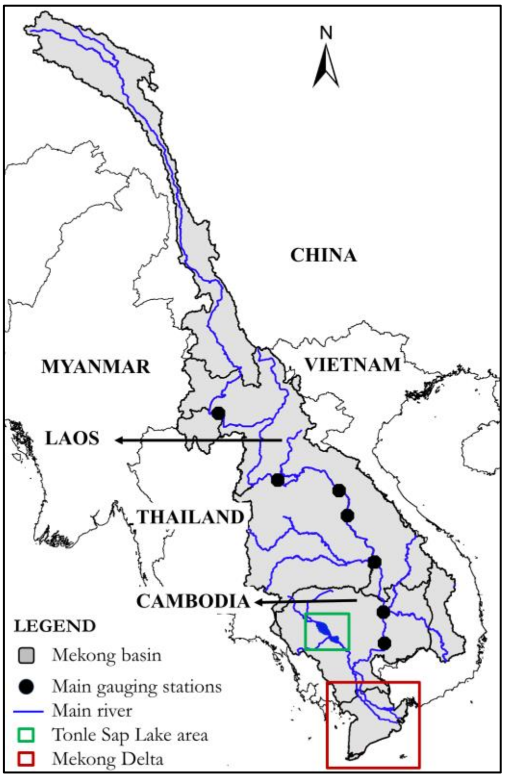

Figure 1.3 Overview map of the Mekong River Basin

[1] Every year, between 50 to 80 km^3 of water flows from the river into Tonle Sap Lake during the wet season. During the dry season, flow starts to reverse and water flows from the lake back into the main river.

The Mekong River's flow regime features two distinct wet (May - November) and dry (December - April) seasons, which are largely determined by the tropical monsoon climate. More than 70% of the total flows are generated during the wet season, showing a highly uneven temporal flow distribution (calculated from MRC, 2005). Additionally, floods and droughts in the Mekong are often associated with the El Niño-Southern Oscillation (ENSO), where droughts tend to occur during El Niño years while floods tend to occur during La Niña years (Räsänen and Kummu, 2013). Recent major droughts occurred in 1992, 1993, 1998, 1999 and 2003-2005 and caused substantial damages to agricultural production, waterway transportation and saltwater intrusion in the downstream Mekong Delta in Vietnam. Extreme floods are also a major safety risk, especially those occurring in the downstream Mekong Delta (MDP, 2013; Marchand et al. 2014). Floods in the Mekong basin are often caused by widespread and heavy rainfalls and the most extreme events often occur when monsoon-driven rainfalls coincide with heavy rainfalls caused by tropical storms. The most recent floods in 2000, 2001, 2002 and 2011 caused hundreds of life losses and severe damages to infrastructures and crops. The historic floods in 2000 and 2011 with estimated economic losses of over US $450 (MRC, 2010) and US $50 (MRC, 2011b) million, respectively, highlight critical flood vulnerability in the downstream Mekong region, especially the Vietnamese Mekong Delta.

The Mekong's flow dynamics and water resources provide important benefits for multiple economic sectors in the basin. The river, especially Lake Tonle Sap and the Vietnamese Mekong Delta, provides about 2.6 million tons of fish annually, which is considered one of the world's highest inland fish catch (Hortle, 2007a). The fishery resources play a crucial role in nutrition and food security in the downstream Mekong region, especially in Cambodia and Vietnam. Current estimates show that fisheries contribute up to 80% of protein intake for millions of people living around Tonle Sap Lake (Baran and Myschowoda, 2009; Arias et al. 2014). Similarly, abundant river flows and nutrient-rich suspended sediment content (estimated at about 150 million tons per year, Kummu et al. 2008) support one of the world's most important rice production areas in the downstream Mekong Delta in Vietnam. Vietnam's rice production, which is primarily contributed from the Mekong Delta, is of special importance for national food security and export revenues (Smajgl et al. 2015). High rice yields (between 4 and 10 tons per crop per ha) not only supply food for Vietnam's 86 million people population but also contribute greatly to the country's position as the 2nd major rice exporter during the last decade (GSO, 2014). Water resources are also becoming increasingly important for other economic sectors, which are accelerating rapidly in all riparian countries, including manufacturing, energy production and domestic water supplies (MRC, 2011a). Values of the Mekong River go beyond economic benefits and livelihood provisions where the river and its water are deeply imbedded in the people's ways of life and cultures. The ancient Angkor civilization (Cambodia) and wet rice culture in the Mekong Delta (in Vietnamese: *văn hóa* *lúa nước*) are typical examples of the strongly linked human-water systems along the Mekong. Important values and high levels of water-dependencies highlight the crucial roles of the Mekong's flows and water resources for local livelihoods, food security and economic developments in the region.

1.5. Thesis outline

The thesis is structured into six chapters. Following a general introduction in Chapter 1, Chapter 2 presents projected changes in the Mekong's flow regimes and hydrological extremes under climate change. The results highlight substantial changes in the flow regime and demonstrate robust evidences of increasing magnitude and frequency of high river flows – suggesting increasing flood hazards under climate change. Chapter 3 broadens the scope of the hydrological impact assessment by adding key anthropogenic factors (i.e. hydropower dam developments and irrigated land expansions). A crop module and a hydropower dam module were integrated to the VMod hydrological model to investigate the combined impacts of multiple driving factors on river flows. Chapters 2 and 3 provide insights about key impacts (i.e. increasing floods) and vulnerability hotspots (i.e. the Mekong Delta), which together shape the research for Chapter 4. This chapter focuses on the Mekong Delta and presents a model chain to assess future flood hazards under upstream climate-change-induced hydrological changes and downstream sea level rise. By using a weather generator and a highly spatially resolved flood model, this chapter provides spatially explicit, probabilistic estimates of the future extreme floods in the low-lying Mekong Delta. The following Chapter 5 also focuses on extreme floods in the Mekong Delta, but shifts focus towards developing adaptation measures and strategies. This chapter presents a diverse set of measures and concrete strategies to adapt to future floods, covering not only the technical interventions but also those to improve the governance and institutional capacities for adaptation. Finally, Chapter 6 synthesizes the main findings and discusses the study's scientific contributions, recommendations for water management and perspectives on future research.

CHAPTER 2

Mekong River flow and hydrological extremes under climate change

Abstract

Climate change poses critical threats to water related safety and sustainability in the Mekong River basin. Hydrological impact signals from earlier Coupled Model Intercomparison Project phase 3 (CMIP3)-based assessments, however, are highly uncertain and largely ignore hydrological extremes. This paper provides one of the first hydrological impact assessments using the CMIP5 climate projections. Furthermore, we model and analyse changes in river flow regimes and hydrological extremes (i.e. high-flow and low-flow conditions). In general, the Mekong's hydrological cycle intensifies under future climate change. The scenario's ensemble mean shows increases in both seasonal and annual river discharges (annual change between +5% and +16 %, depending on location). Despite the overall increasing trend, the individual scenarios show differences in the magnitude of discharge changes and, to a lesser extent, contrasting directional changes. The scenario's ensemble, however, shows reduced uncertainties in climate projection and hydrological impacts compared to earlier CMIP3-based assessments. We further found that extremely high-flow events increase in both magnitude and frequency. Extremely low flows, on the other hand, are projected to occur less often under climate change. Higher low flows can help reducing dry season water shortage and controlling salinization in the downstream Mekong Delta. However, higher and more frequent peak discharges will exacerbate flood risks in the basin. Climate change-induced hydrological changes will have important implications for safety, economic development, and ecosystem dynamics and thus require special attention in climate change adaptation and water management.

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2.1. Introduction

The Mekong River basin is one of the most important transboundary rivers in Southeast Asia. Starting from the Tibetan Plateau, the 4800 km long river flows across six different countries, namely China, Myanmar, Laos PDR, Thailand, Cambodia, and finally Vietnam before draining into the East Sea (also known as South China Sea). The economies and societies along the Mekong are strongly linked to its abundant water resources (Mekong River Commission – MRC, 2010). The most important water-dependent economic sectors include agriculture, energy (i.e. hydropower production), and fishery (Västilä et al. 2010; MRC, 2011a). Currently, the Mekong basin is home to about 70 million people and this population is expected to increase to 100 million by 2050 (Varis et al. 2012). Economic development has been accelerating rapidly over the last decades together with substantial increases in water resources use (Jacobs, 2002; Lebel et al. 2005; Piman et al. 2013). Given high dependencies on water in the basin, the issues of securing water safety and long-term sustainability are especially important for water resources management.

Socio-economic developments in the Mekong River basin, however, are facing critical challenges relating to water resources, including hydrological changes caused by climate change (Keskinen et al. 2010; MRC, 2010; Västilä et al. 2010). Existing studies (e.g. Eastham et al. 2008; Hoanh et al. 2010; Västilä et al. 2010) suggest that climate change will alter the current hydrological regime and thus posing challenges for ecosystems and socio-economic developments. For instance, Västilä et al. (2010) and Hoanh et al. (2010) modelled the Mekong's flow regimes under several climate change scenarios and suggested a likely intensification of the hydrological cycle, resulting in increases in annual and seasonal river discharges. Consequently, they also suggest increasing flood risks during the wet season in the Cambodian and Vietnamese floodplain due to increasing river flow. Other studies (e.g. Lauri et al. 2012; Kingston et al. 2011) also suggest possible discharge reduction in the dry season under some individual climate change scenarios.

Although many studies about climate change impacts on the Mekong's hydrology exist, two major challenges in understanding hydrological responses to climate change remain. First, existing hydrological impact assessments prove highly uncertain. In particular, impact signals differ markedly in the magnitudes and even directions of changes across the individual global circulation models (GCMs) and climate change scenarios. Kingston et al. (2011) quantified uncertainties related to the choice of GCMs and climate scenarios in projecting monthly discharge changes and show a large range between -16 and +55 %. They also noted that hydrological changes under different GCMs and scenarios differ remarkably in magnitude and even in contrasting directions. Another study by Lauri et al. (2012) also reported a wide range of discharge change between -11 and +15% during the rainy season and between -10 and +13% during the dry season. Both studies noted the uncertainty in hydrological impact signals, which is mainly associated with uncertainties in the climate change projection, especially precipitation changes. Given these uncertainties, they all also stress the importance of using multiple GCMs and several scenarios (i.e. an ensemble approach) rather than relying on a single model or climate change projection. Compared to uncertainties in the future climate, uncertainties relating to hydrological models' schematization and parameterization seem less important for the Mekong basin. Regarding hydrological models' skill, many studies including Hoanh et al. (2010), Västilä et al. (2010), Kingston et al. (2011), and Lauri et al. (2012) reported sufficient performance in capturing the dynamics of the Mekong's hydrology. Several previous studies also reported lower modelling skill in the upstream stations (e.g. Chiang Saen) compared to the downstream stations (Kingston et al. 2011; Lauri et al. 2012; Wang et al. 2016).

Notably, all earlier studies are based on the SRES emission scenarios (Nakicenovic et al. 2000), which were used in the Coupled Model Intercomparison Project phase 3 (CMIP3). These scenarios, which only include non-intervention scenarios, have recently been replaced by the Representative Concentration Pathways (RCPs) scenarios (Van Vuuren et al. 2011; Stocker et al. 2013), resulting in a broader range of climate change. These most recent climate change scenarios (i.e. the CMIP5) are not yet routinely used to assess the hydrological impacts in the Mekong basin. The CMIP5 scenarios also exhibit important improvements, both in terms of the GCMs' technical development (Taylor et al. 2011; Knutti and Sedláček, 2013) and the efficiency to reproduce the historic climate conditions (Hasson et al. 2016). These important improvements and updates are highly relevant and require one to update the hydrological projections for the Mekong. In this study, we will do this update and reflect whether the CMIP3 uncertainties relating to the hydrological signal will be reduced as well.

Second, although hydrological extremes under future climatic change are very relevant for water management and climate change adaptation (Piman et al. 2013; Cosslett and Cosslett, 2014), very few insights have been gained on this topic so far in the Mekong. Previous studies typically analysed hydrological changes at monthly and seasonal timescales and few studies focused on changes in frequency and severity of extreme events (i.e. climate-change-induced floods and droughts). This knowledge gap also relates to the fact that uncertainties, especially those relating to future monsoon and precipitation changes, prevail in the CMIP3 climate change projections. Given high level of policy relevance and important improvements in CMIP5 climate change projections, future changes in extreme high and low river flows should be comprehensively assessed and made available to decision makers.

In this paper, we aim to address these knowledge gaps in understanding the Mekong's hydrology under climate change. A distributed hydrological model was set up and calibrated for the whole Mekong River (Sections 2.3.1 and 2.4.1). We selected a set of 10 climate change experiments for five GCMs and two RCPs from the CMIP5 and performed a downscaling and bias correction on the climate model output (Section 2.3.2). Future changes in precipitation and temperature (Section 2.4.2) and subsequently the Mekong's annual and monthly discharge changes were quantified (Section 2.4.3). In addition, we quantified changes in hydrological extremes, focusing on both extreme low and high flows (Section 2.4.4). We will also reflect on the robustness of the hydrological signals and show improvements in uncertainty compared to other CMIP3-based studies (Section 2.5.1).

2.2. The Mekong River basin

The Mekong (Figure 2.1) is an average-sized river basin compared to other major rivers of the world. Its total drainage area is about 795 000 km^2, distributed unevenly across six Southeast Asian countries (MRC, 2005). The river's annual discharge volume of 475 km^3, is considerably higher than similarly sized river basins. Despite its moderate area, the Mekong ranks tenth in terms of annual discharge volume (Dai and Trenberth, 2002). This implies that the basin receives higher precipitation amount per unit area, owing to its dominant tropical monsoon climate (Adamson et al. 2009; Renaud et al. 2012). Elevation in the basin ranges between above 5000m in the Tibetan Plateau to only a few metres above sea level in the downstream river delta.

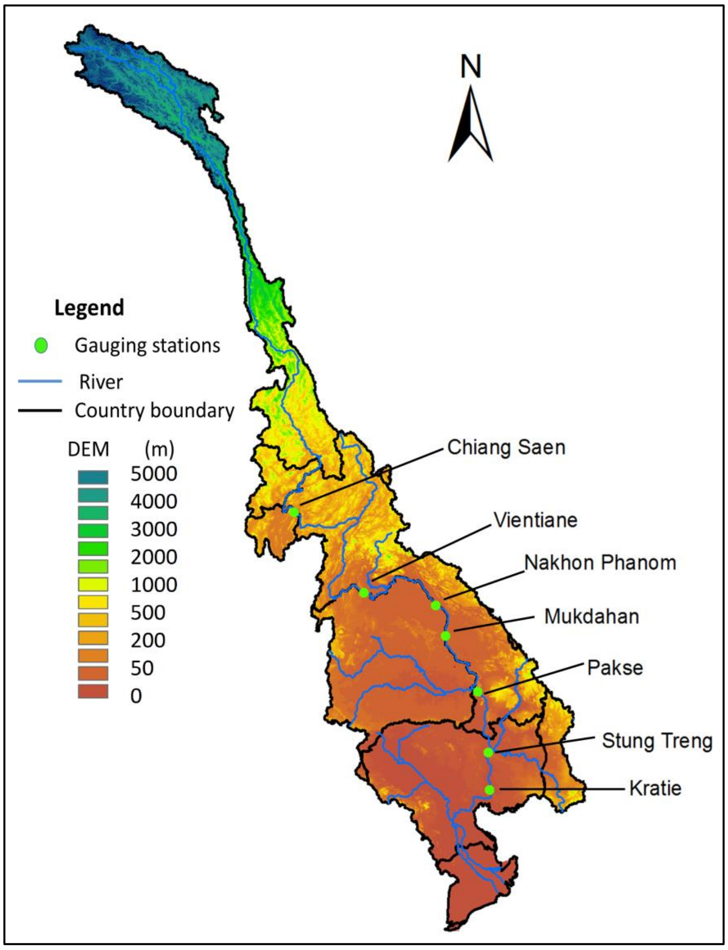

Figure 2.1 The Mekong River basin's elevation map and locations of mainstream gauging stations

The Mekong's hydrological regime is largely driven by monsoonal activities, most importantly the south-west monsoon and to a lesser extent the north-east monsoon (Costa-Cabral et al. 2008; MRC, 2009a; Delgado et al. 2012). The south-west monsoon is dominant from May to September, whereas the north-east monsoon is active from November to February. These monsoonal activities characterize the basin's hydrology into two hydrological seasons with distinctive flow characteristics. A substantially larger proportion of the annual flow is generated during the wet seasons (June–November). Depending on location, the wet season flow accounts for between 75 and 85% of the total annual flow (calculated from MRC, 2005). Seasonal variation in river flow, especially the flood pulse occurring in the downstream delta (i.e. the Tonle Sap Lake in Cambodia and the Vietnamese Mekong delta), supports a highly productive aquatic ecosystem and one of the world's major rice production areas (Lamberts and Koponen, 2008; Arias et al. 2012).

Hydrological changes, including changes in extreme high and low flows, increase safety risks and undermine economic productivity in the basin, especially in the low-lying river delta (Eastham et al. 2008; Arias et al. 2014). Extreme floods caused by intensive and widespread precipitation events result in vast inundation thereby damaging crops, infrastructure, and, in very extreme cases (e.g. flood events in 2000 and 2011), disrupting how the whole downstream delta functions. The catastrophic flood in 2000 with an estimated total economic loss of over USD200 million (Cosslett and Cosslett, 2014) illustrates the severe flood damage that can occur in this area. Extreme low flows also affect agriculture production, which largely depends on surface water irrigation in many parts of the basin. Lack of upstream inflow during the dry season also exacerbates the risk of saltwater intrusion, affecting the downstream delta's ecosystems, domestic water supply, and agricultural production (Smajgl et al. 2015).

2.3. Methodology

2.3.1. Hydrological model

VMod (Lauri et al. 2006) is a distributed hydrological model using a square grid representation of river basins. This grid uses multiple raster layers containing data for flow direction, river network, soil, and land use. The simulation process starts with interpolating climate input for each grid cell from climate input data. VMod requires minimally four daily climate forcing variables (i.e. maximum, minimum, and average air temperatures, and precipitation). Climate forcing data are calculated for each grid cell using an inverse distance weighted interpolation. Potential evapotranspiration (PET) is calculated using the Hargraeves–Samani method (Hargraeves and Samani, 1982), where PET is calculated using daily maximum and minimum temperatures, latitude, and calendar day of the year. The soil is simulated as two distinctive layers and soil surface processes are simulated following Dingman (1994). After calculating the water balance, runoff is routed from cell to cell and finally into the river network. A detailed description of the VMod model's algorithms and equations is available in the model's manual (Lauri et al. 2006).

In this study, we used the modelling set-up for the Mekong River basin from Lauri et al. (2012). This Mekong modelling set-up was prepared from several soil, land use, and elevation data sets, allowing for daily hydrological simulation at 5 km x 5 km spatial resolution. Soil data were prepared from the FAO soil map of the world (FAO, 2003). Soil data were prepared by first reclassifying the original data into eight classes and then aggregated to a 5 km x 5 km grid. Land use data were prepared by reclassifying the original Global Land Cover 2000 data (GLC2000, 2003) into nine classes and then aggregated to the model's grid. The GLC2000 provides land cover data that are most suitable to our calibration and validation time period (i.e. 1981–2001). The flow direction data were prepared from the SRTM90m elevations (Jarvis et al. 2008). The elevation data along the main river's branches were adjusted to force these branches into the proper flow direction. More detailed information on the model set-up and its parameterization for the Mekong basin is available in Lauri et al. (2012).

We calibrated and validated the hydrological model against observed daily river discharges at seven gauging stations: Chiang Saen, Vientiane, Nakhon Phanom, Mukdahan, Pakse, Stung Treng, and Kratie (Figure 2.1). Observed discharge data were obtained from the Mekong River Commission's hydrological database (MRC, 2011c). Calibration and validation periods are 1981–1991 and 1991–2001, respectively. The hydrological model's performance was assessed using discharge plots and model performance indices. In particular, the daily river discharges plots and the flow duration curves (Vogel and Fennessey, 1995) were used to visually check the goodness of fit between observed and simulated data. Furthermore, the Nash–Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) and relative biases indices were used to quantify the model's performance during calibration and validation. The model's over- and underestimation of total annual river discharge, high-flow, and low-flow indices (i.e. Q5 and Q95, respectively) were assessed by calculating the relative biases. These Q5 (high flow) and Q95 (low flow) are commonly used indices in hydrological analyses, defined as the values that exceed the discharge time series data by 5 and 95% of the time, respectively. The biases are calculated as simulated values divided by observed values under the same time period of interest.

We started the model calibration by using the initial parameterization from Lauri et al. (2012). Simulation performance was further improved by manually adjusting several model's parameters. In particular, discharge amount and timing at key stations were calibrated to better match with observed data by changing the two soil layers' depth and their water storage capacities. Vertical and horizontal infiltration rates were also adjusted to further improve simulations of high flows and low flows. Lastly, snowmelt rate and temperature thresholds for snow precipitation and snowmelt were adjusted to improve model performance at the upper catchment above Chiang Saen (northern Thailand). All parameter values were adjusted within the physically realistic range described in Lauri et al. (2006) and Sarkkula et al. (2010).

2.3.2. Climate data

We prepared climate data for the historic period (1971–2000) and the future period (2036–2065) using various data sets. Historic temperature was prepared from the WATCH forcing data (Weedon et al. 2011), which is a global historic climate data set for the 1958–2001 period, produced from the 40-year ECMWF Re-Analysis (Uppala et al. 2005) and bias corrected using the CRU-TS2.1 observed data (Mitchell and Jones, 2005). This data set is widely used in various global and regional studies (e.g. van Vliet et al. 2013; Leng et al. 2015; Veldkamp et al. 2015). Precipitation data were extracted from the

APHRODITE data set (Yatagai et al. 2012), which is an observation-based precipitation data set, developed from a high-density network of rain gauges over Asia. This data set has been evaluated as one of the best gridded precipitation data sets for hydrological modelling purposes in the Mekong basin (Lauri et al. 2014). We further discuss potential implications of using the combined WATCH-APHRODITE data in Section 2.5.3.

We used the most recent CMIP5 climate projection to develop climate change scenarios. The scenarios were developed for the 2036–2065 period, i.e. mid-21st Century, which is a relevant time frame for long-term water resources planning and adaptation (MRC, 2011a). Since the regional climate model data of the Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi and Gutowski, 2015) so far only covers one GCM for the Mekong region, we decided to use GCM projections as basis for this climate impact assessment. We therefore downscaled the GCM projections ourselves. Given the relatively large number of GCMs under CMIP5, we first did a model selection by reviewing literature on GCM performance. We selected those GCMs that better reproduce historic tropical temperature and precipitation conditions, implying their suitability to be used in the Mekong region. For historic temperature simulations, Huang et al. (2014) assessed the CMIP5 models efficiency for the Mekong basin and suggested BCC-CSM1-1, CSIROMK3-6-0, HadGEM2-ES, and MIROC-ESM-CHEM as the better-performing models. Hasson et al. (2016) evaluated the GCM's performance in simulating seasonal precipitation focusing on monsoonal activities for three major river basins in South and Southeast Asia, including the Mekong. They concluded that the MPI models, MIROC5 and CSIRO-Mk3-6-0, CCSM4, CESM1-CAM5, GFDL-ESM2G, IPSL-CMAMR, MIROC-ESM, and MIROC-ESM-CHEM perform better than other GCMs in the assessment. Furthermore, we also consulted the model evaluation of Sillmann et al. (2013) to represent climate extremes. They indicated that ACCESS-1.0, CCSM4, MPI models, and HadGEM2-ES are amongst the better-performing models. Based on these GCM evaluations, we selected five GCMs for this study (Table 2.1). For each GCM, we extracted climate data for two different RCPs, namely RCP4.5 and RCP8.5. The RCP4.5 is a medium to low scenario assuming a stabilization of radiative forcing to 4.5W m^{-2} by 2100 (Thomson et al. 2011). The RCP8.5 is a high radiative-forcing scenario assuming a rising radiative forcing leading to 8.5W m^{-2} by 2100 (Riahi et al. 2011). By selecting a mid-range and a high-end scenario, we expect to capture a reasonable range in climatic and hydrological projections for the Mekong basin. Given our focus on hydrological extremes under climate change, we did not consider RCP2.6, which is the lowest radiative-forcing scenario.

Table 2.1 Selected CMIP5 GCMs for climatic and hydrological change assessment

GCM name	Acronyms	Institution	Resolution (long x lat)
ACCESS1-0	ACCESS	CSIRO-BOM - Commonwealth Scientific and Industrial Research Organisation, Australia and Bureau of Meteorology, Australia	1.875° x 1.25°
CCSM4	CCSM	NCAR - National Center for Atmospheric Research	1.25° x 0.94°
CSIRO-Mk3.6.0	CSIRO	CSIRO-QCCCE - Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	1.875° x 1.875°
HadGEM2-ES	HadGEM	MOHC - Met Office Hadley Centre and Instituto Nacional de Pesquisas Espaciais	1.875° x1.24°
MPI-ESM-LR	MPI	MPI-M Max Planck Institute for Meteorology	1.875° x1.875°

Since the GCMs' spatial resolution is generally too coarse for a basin-scale study, we re-gridded the climate data to a 0.5° x 0.5° grid using bilinear interpolation. Subsequently, the data are subjected to a statistical bias correction, using the method developed by Piani et al. (2010) to correct biases in the GCM simulations. This bias-correction is done by developing transfer functions, which match the GCM historic (1959–2000) data's monthly statistics to an independent, observed climatology. We used the WATCH forcing data and APHRODITE as independent data sets. The developed transfer functions were then applied on the future climate data to correct the biases in the GCM's future climate projection. Detailed information on the bias-correction method is available in Piani et al. (2010).

2.3.3. Analysing hydrological changes

We employed several techniques to analyse different aspects of hydrological changes. First, annual and monthly discharge statistics were calculated to understand changes in the river's flow regime. Second, we calculated the Q5 and Q95 to analyse changes in high-flow and low-flow conditions, respectively. Lastly, we fitted discharge data to suitable extreme value distributions to investigate the magnitude and frequency of extreme high flows and low flows. Yearly peak river discharges data were fitted to the generalized extreme value distribution (Stedinger et al. 1993; Dung et al. 2015). Similarly, maximum cumulative discharge deficit, defined as the total deficit under a threshold, were fitted to the generalized Pareto distribution (Tallaksen et al. 2004; Hurkmans et al. 2010) to analyse extreme low flows. The threshold to calculate cumulative discharge deficit is defined as Q75 (discharge value exceeded 75% of the time) under future climate change (Hisdal et al. 2004). Hydrological changes were calculated under individual scenarios and under ensembles, i.e. average changes from multiple GCMs and both RCPs.

2.4. Results

2.4.1. Performance of the hydrological simulations

The calibration and validation results are presented in Table 2.2. The simulated river discharges in general match relatively well to the observed data. The NSE values show very good performance (0.88–0.96) for all considered stations. Similarly, the relative biases in total discharge, and the high-flow (Q5) and low-flow (Q95) indices are all within acceptable ranges, except for relatively lower performance at the most upstream Chiang Saen station. Discharge biases show underestimation of annual discharge at Chiang Saen by 10 and 12% during the calibration and validation, respectively. This underestimation is also shown by the flow duration curve, where simulated low flows exhibit more biases than high flows (Figure 2.2). Low-flow biases at Chiang Saen could be explained by unaccounted flow regulation by upstream hydropower dams during the dry season, as suggested by Adamson (2001), Lauri et al. (2012) and Räsänen et al. (2012). Lower accuracy of the APHRODITE precipitation data above Chiang Saen could also affect the model's performance. Rainfall data quality is probably affected by strong orographic effects and by a relatively low rain gauge density in this area (Lauri et al. 2014). Discharge biases, however, are only substantial at Chiang Saen station and quickly improve further downstream (see Table 2.2). Lastly, daily discharge plots also show good matches between simulated and observed discharges for both calibration and validation periods (Figure 2.2). Based on these validations, we conclude that the model set-up is suitable for our modelling purposes.

Table 2.2 Model performance indices calculated from daily time series for calibration (C) and validation (V) periods. See station locations in Figure 2.1.

Stations	NSE		Relative total flow bias		Q5 high flow relative bias		Q95 low flow relative bias	
	C	V	C	V	C	V	C	V
Chiang Saen	0.90	0.90	0.90	0.88	0.93	0.91	0.64	0.62
Vientiane	0.92	0.88	1.08	1.10	1.12	1.14	0.85	0.81
Nakhon Phanom	0.96	0.96	1.03	1.03	1	0.85	0.92	0.72
Mukdahan	0.96	0.95	0.98	1	0.96	0.89	0.81	0.7
Pakse	0.94	0.94	0.94	0.91	0.88	0.88	0.89	0.82
StungTreng	0.94	0.97	0.93	0.89	0.86	0.84	1.09	0.86
Kratie	0.95	0.93	1.00	0.90	0.91	0.85	1.01	0.83

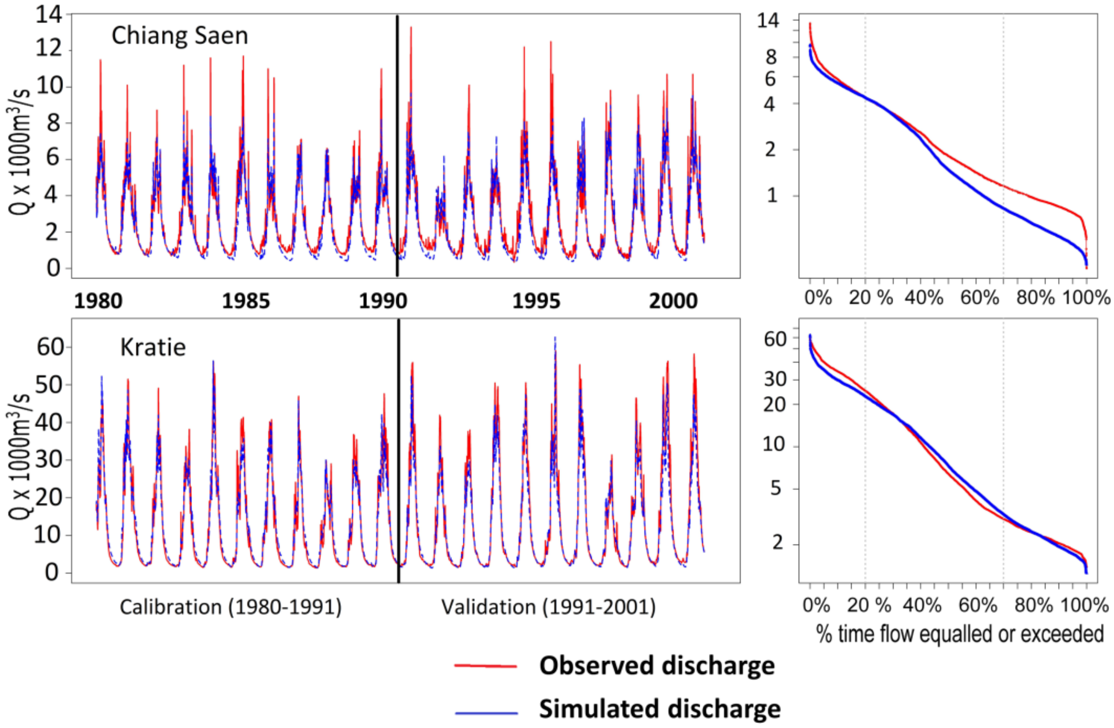

Figure 2.2 Daily discharge plots (left) and flow duration curves (right) during calibration and validation at Chiang Saen (upper plots) and Kratie (lower plots). See station locations in Figure 2.1

2.4.2. Climate change projection

We analysed future changes in temperature and precipitation projected by the GCMs and RCPs by comparing climate data between the baseline (1971–2000) and future (2036–2065) periods. Since we only assessed hydrological changes down to Kratie (Cambodia), we excluded the downstream area below this station (i.e. south of latitude 12.5° N) when calculating temperature and precipitation changes.

Overall, surface air temperature increases consistently under all GCMs and RCPs (Figure 2.3). All GCMs project higher temperature increase in the RCP8.5 than in the RCP4.5. In particular, the RCP8.5 ensemble shows an increase of +2.4 °C whereas the RCP4.5 ensemble projects +1.9 °C. Temperature increase differs amongst the individual GCMs and RCPs. The lowest basin-average temperature increase of 1.5 °C is projected by the MPI-RCP4.5, whereas the ACCESS-RCP8.5 projects the highest increase of 3.5 °C. A majority of scenarios project temperature increases between 1.5 °C and 2.5 °C, including CCSM-RCP8.5, CSIRO-RCP4.5, CSIRO-RCP8.5, HadGEM-RCP4.5, HadGEM-RCP8.5, and MPI-RCP4.5. Notably, the ACCESS GCM shows markedly more temperature increase compared to other models. The spatial patterns of temperature increases are relatively similar between the scenarios: temperature tends to increase more in the upper catchment area in China, large parts of Thailand, and sometimes also in the Vietnamese Mekong delta (Figure 2.3). Areas with lower future temperature increases are located mostly in the eastern part of the Mekong's lower basin including eastern Cambodia and the central highlands of Vietnam.

Total annual precipitation in the Mekong basin is projected to increase under most (i.e. 9 out of 10) climate change scenarios. Only the HadGEM-RCP8.5 scenario projects a slight reduction (i.e. -3 %) in annual precipitation. Annual precipitation changes between -3 % (HadGEM-RCP8.5) and +5 % (CCSM-RCP8.5), with an ensemble mean of +3 % across all the scenarios. The scenarios also show larger range of basin-wide precipitation changes under the RCP8.5 (i.e. between -3 and +5 %) compared to that under the RCP4.5 (i.e. between +3 and +4 %). Notably, these ranges of precipitation changes are typically smaller than those derived from earlier CMIP3-based assessments (i.e. Eastham et al. 2008; Kingston et al. 2011; Lauri et al. 2012; Thompson et al. 2013). Details on cross-study comparisons are shown in Table 2.4. Reduced uncertainties in precipitation projection will likely improve the robustness of the projected hydrological changes.

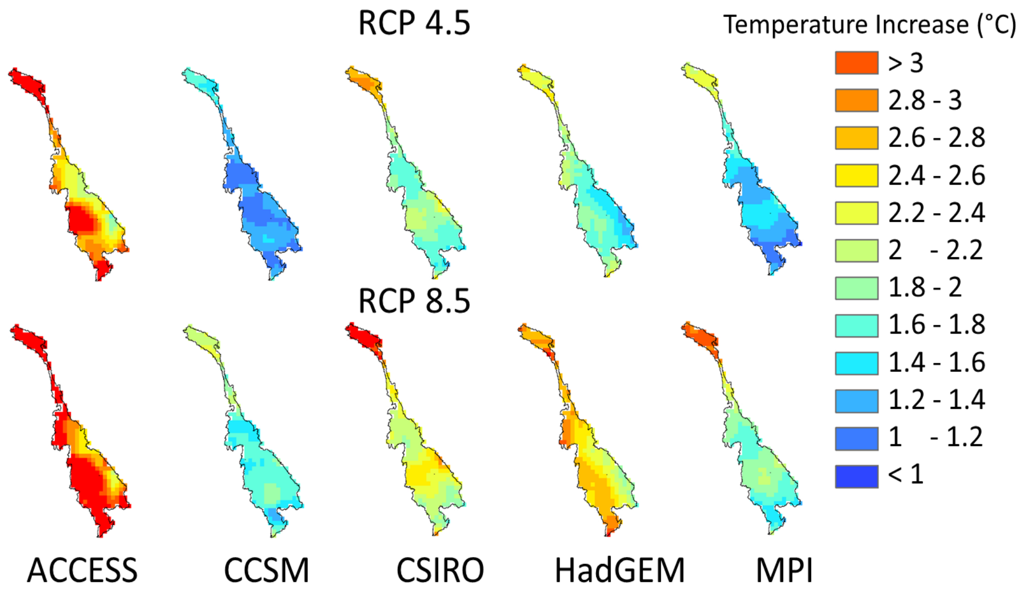

Figure 2.3 Projected change in daily mean temperature (°C) under future climate (2036-2065) compared to baseline situation (1971-2000).

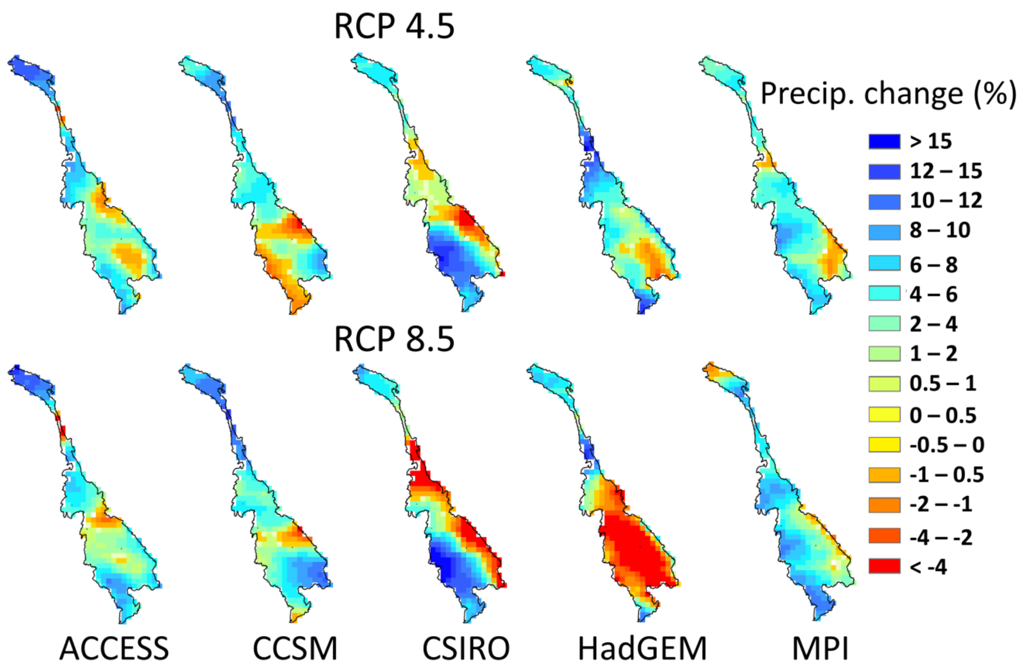

Figure 2.4 Projected change in total annual precipitation (%) under future climate (2036-2065) compared to the baseline climate (1971-2000).

Despite the overall increasing signal, all scenarios project contrasting directional changes where precipitation increases in some areas and reduces in others (Figure 2.4). The upper catchment area (i.e. above Chiang Saen) exhibits substantial precipitation increase under all scenarios. The lower Mekong area, on the other hand, shows both increase and reduction in annual rainfall, depending on location. Many GCMs, including CSIRO, HadGEM, and MPI, project rainfall reduction in the eastern part of the lower Mekong basin (i.e. southern Laos PDR, eastern Cambodia, and the Vietnamese central highlands), especially under the RCP8.5 scenario.

2.4.3. Changes in the flow regime

This section presents changes in annual, seasonal, and monthly river discharges under climate change. Annual changes are presented for all seven mainstream stations (see locations in Figure 2.1) while we limit the rest of the results to three representative stations to maintain the paper's focus. These stations are Vientiane (Laos PDR), Mukdahan (Thailand), and Kratie (Cambodia), each representing the upper, middle, and lower parts of the basin, respectively.

Table 2.3 Relative changes in annual river discharges at the Mekong's mainstream stations for 2036-2065 relative to 1971-2000. Lowest and highest changes are presented with the corresponding climate change scenarios.

Station	RCP 4.5		RCP 8.5	
	Ensemble mean (%)	Range (%)	Ensemble mean (%)	Range (%)
Chiang Saen	+14	+4 - +29 CSIRO - ACCESS	+15	-1 - +33 CSIRO - ACCESS
Vientiane	+9	+1 - +17 CSIRO - ACCESS	+9	-1 - +20 CSIRO - ACCESS
Nakhon Phanom	+7	-1 - +12 CSIRO - ACCESS	+6	-2 - +13 CSIRO – ACCESS
Mukdahan	+6	-1 - +11 CSIRO - ACCESS	+5	-4 - +13 HadGEM - ACCESS
Pakse	+6	+2 - +10 CCSM - ACCESS	+5	-6 - +13 HadGEM - MPI
Stung Treng	+5	+3 - +8 CCSM - ACCESS	+5	-7 - +10 HadGEM - ACCESS
Kratie	+5	+3 - +8 CCSM - ACCESS	+5	-7 - +11 HadGEM - MPI

The GCM ensemble mean, lowest, and highest changes in annual river discharge are presented in Table 2.3 for both RCPs. The ensemble means in both the RCP4.5 and the RCP8.5 show a general increase of the Mekong's mean flow under climate change. Annual discharges increase between +5% (at Kratie and Stung Treng) and +15% (at Chiang Saen), indicating a more substantial increase in the upstream stations compared to the downstream ones. Despite the general increasing signal based on ensemble mean, annual discharges also reduce slightly under some individual scenarios. The reductions range from -1% (at Chiang Saen, scenario CSIR0-RCP4.5) to +7% (at Stung Treng and Kratie, scenario HadGEM-RCP8.5). While the ensemble means under the two RCPs are very similar, the RCP8.5 exhibits a larger range in projected discharge changes (Table 2.3). This larger range is associated with more differentiated precipitation changes under individual GCMs in the RCP8.5 compared to those in the RCP4.5 (see Figure 2.4).

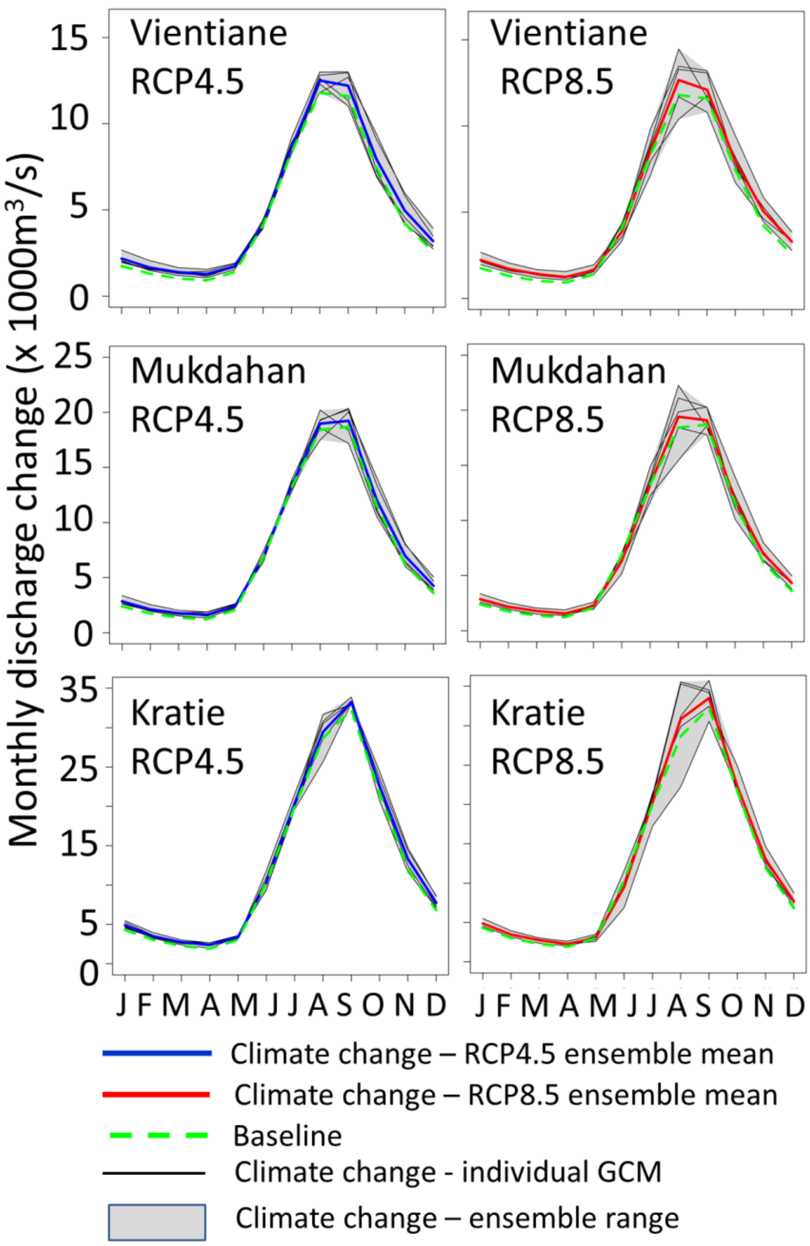

Figure 2.5 Projected monthly river discharge under climate change for 2036-2065 relative to 1971-2000.

Figure 2.5 shows changes in monthly river discharges under climate change. Overall, the scenario ensembles show higher monthly river flow at all considered stations, except for a slight reduction in June. Absolute discharge increases are more substantial in the wet season compared to those in the dry season. In terms of timing, the RCP4.5 shows the largest increases in November, while the RCP8.5 shows the largest increase in August. Although absolute increases are more substantial during the wet season months, relative increases are higher during the dry season. For instance, discharge in April could increase up to +40% (+360 m^3 s^{-1}) at Vientiane and +25% (+480 m^3 s^{-1}) at Kratie. Despite the overall increasing trends, discharge in June is projected to reduce slightly at all three stations, ranging between -810 $m^3 s^{-1}$ (-8 %) at Kratie, followed by -530 $m^3 s^{-1}$ (-8 %) at Mukdahan and -210 $m^3 s^{-1}$ (-5 %) at Vientiane. On the seasonal timescale, discharges increase at all stations during both the wet and dry seasons.

Cross-GCM comparisons show that monthly discharge changes during the wet season are more variable compared to the dry season. Figure 2.5 clearly shows that the ensemble's projection ranges become markedly larger in the wet season, implying higher uncertainty in the hydrological change signal. For example, projected river discharge in August at Mukdahan ranges between 15 400 $m^3 s^{-1}$ (scenario HadGEMRCP8.5) and 22 300 $m^3 s^{-1}$ (scenario MPI-RCP8.5). This is a spread of 6900 $m^3 s^{-1}$, equivalent to 36% of the average discharge in August. Moreover, the individual GCMs also show contrasting directional discharge changes in the wet season months. The CSIRO and HadGEM models project reductions in discharge during June–October, whereas the other models project discharge increases during the same period. These contrasting directional changes mainly result from the disagreement among GCMs on the future precipitation regime in the Mekong basin. This disagreement highlights one of the key uncertainties in projecting future climatic change and subsequently hydrological responses in the Mekong basin, as also noted by Kingston et al. (2011).

2.4.4. Changes in hydrological extremes

This section subsequently presents changes in Q5 (high flow), Q95 (low flow), and hydrological extremes. Relative changes in high flows (Q5) and low flows (Q95) at Vientiane, Mukdahan, and Kratie are shown in Figure 2.6. Overall, high flows are projected to increase at all considered stations. The scenario ensemble means show increases in Q5 of +8, +5, and +6% at Vientiane, Mukdahan, and Kratie, respectively. However, high flows also slightly reduce in two scenarios. In particular, the CSIRO-RCP8.5 projects high-flow reduction at Vientiane (-6%) and Mukdahan (-3%). Similarly, the HadGEM-RCP8.5 also suggests reductions of -1, -2, and -4% of high flows at Vientiane, Mukdahan, and Kratie, respectively. Low flows are projected to increase under all considered scenarios, implying more water availability during the dry season. On average, Q95 increases most substantially at Vientiane (+41 %), followed by Mukdahan (+30 %) and Kratie (+20 %).

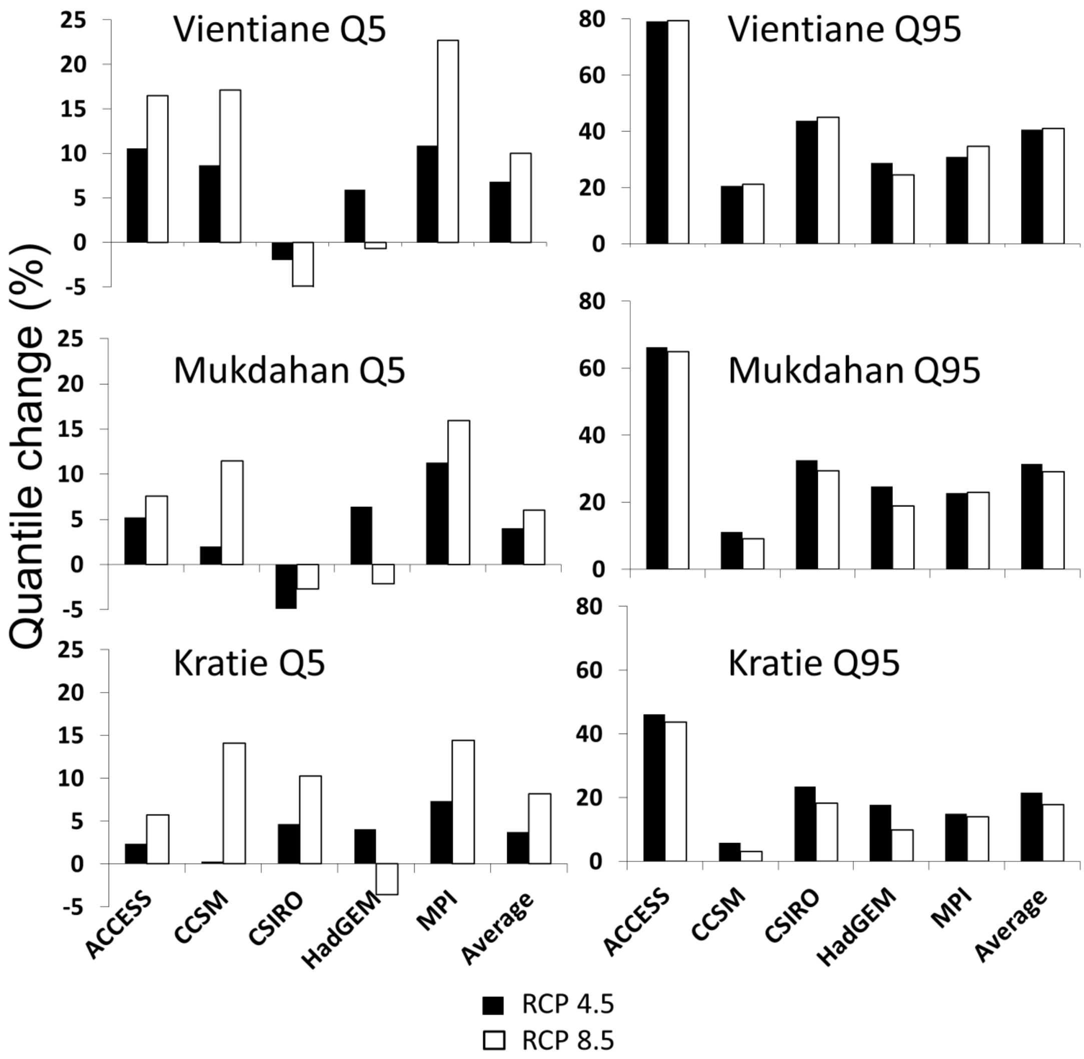

Figure 2.6 Projected changes in Q5 (high flow) and Q95 (low flow) under climate change for 2036-2065 relative to 1971-2000.

The non-exceedance curves of yearly peak discharges (Figure 2.7) show substantial increases in extremely high flow at all considered stations. The baseline's non-exceedance curves are always lower than those from the GCM ensemble means, implying increases in both the magnitude and frequency of annual peak flows. At Vientiane, for instance, the maximum river discharge occurring once every 10 years is projected to increase from 23 800 to 27 900 m^3 s^{-1} (RCP4.5) and 28 500 m^3 s^{-1} (RCP8.5). Similarly, yearly peak discharges at Kratie increase from 61 700 to 65 000 m^3 s^{-1} (RCP4.5) and 66 900m^3 s^{-1} (RCP8.5).

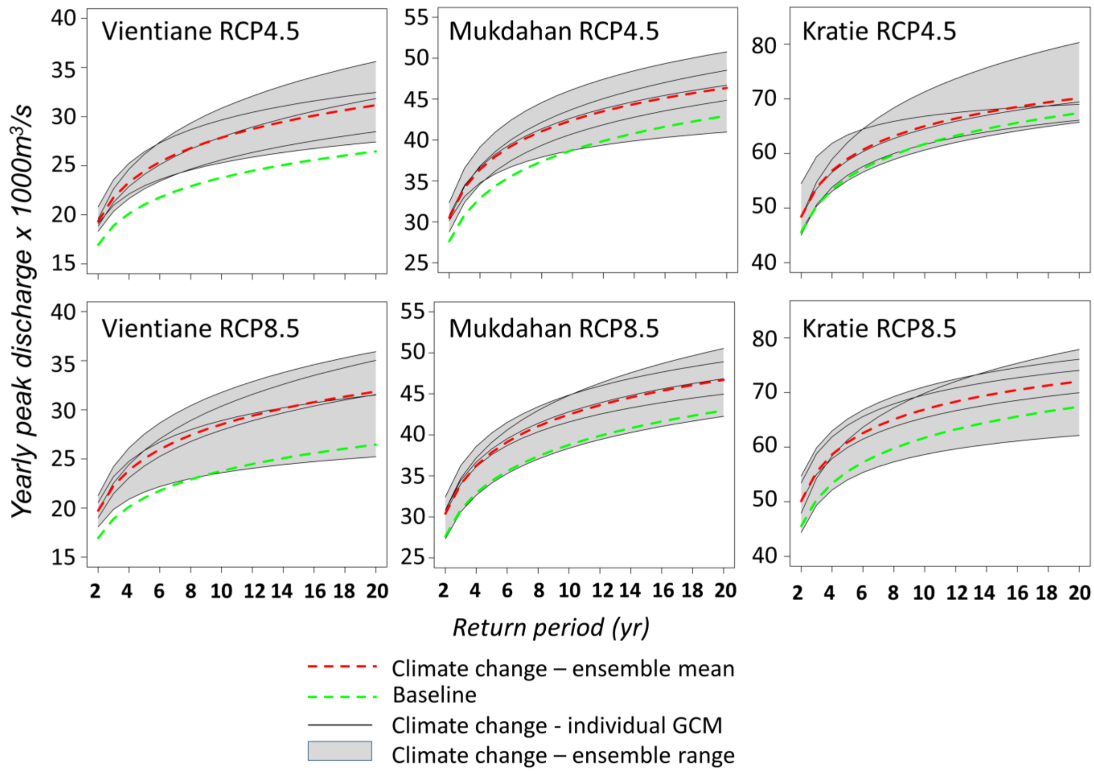

Figure 2.7 Non-exceedance curves of yearly peak discharges under baseline (1971-2000) and future climate (2036-2065).

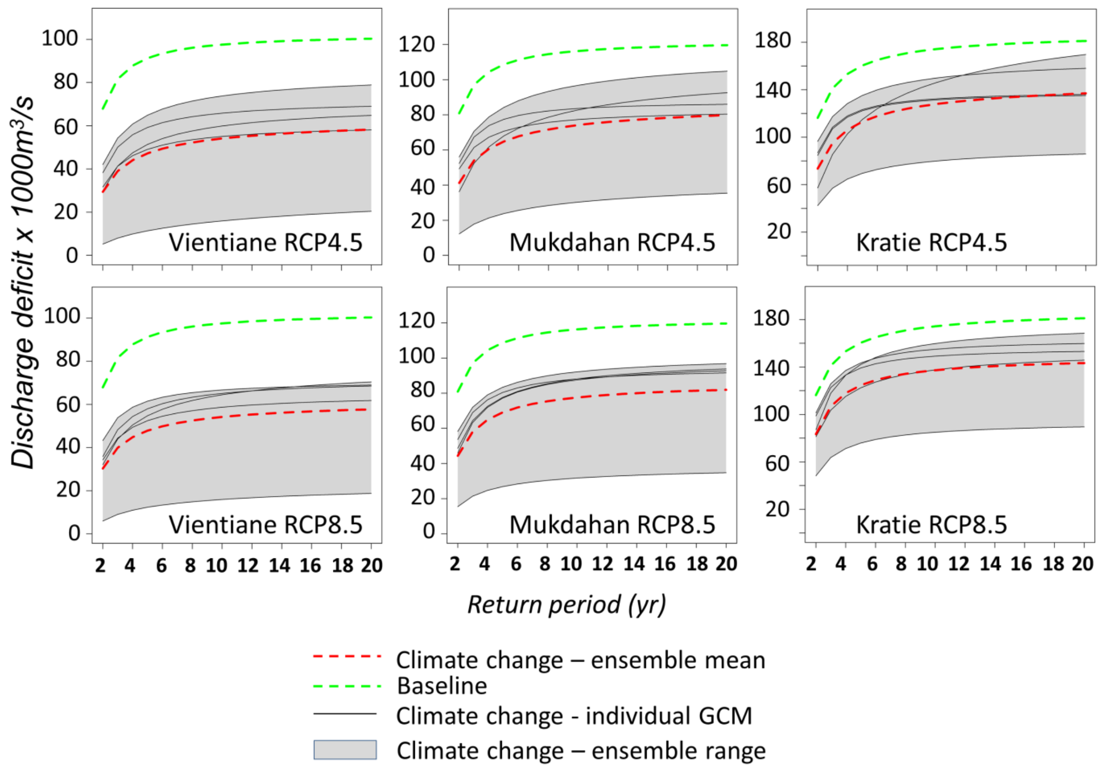

Figure 2.8 Non-exceedance curves of yearly maximum cumulative discharge deficits (i.e. total deficit below the Q75 threshold) under baseline and future climate

Lastly, both magnitude and frequency of extremely low flows are projected to reduce due to more water availability during the dry season. Higher dry season discharge results in reductions in the total discharge deficits, defined as the total deficit under a threshold (Q75 value under climate change). The non-exceedance curves in Figure 2.8 shows that these deficits reduce substantially at all three representative stations. Discharge deficits are lowest at Vientiane, ranging between 68,000m^3 s^{-1} (2-yr return period) and 100 000 m^3 s^{-1} (20-yr return period) under the baseline condition. These deficits are projected to reduce by almost 50%, to 30 000 and 58 000 m^3 s^{-1} under the RCP8.5 scenario. Similarly, discharge deficits also reduce substantially at Mukdahan and Kratie. Figure 2.8 also shows that future discharge deficits are relatively similar between the RCP4.5 and the RCP8.5.

2.5. Discussion

We have presented climatic and hydrological changes in the Mekong River basin based on a relatively large ensemble of CMIP5 GCMs and climate change scenarios. Motivated by improvements in CMIP5 GCMs technicalities and performance, we further analysed changes in extreme hydrological conditions under climate change. As such, our results provide important updates and new insights to the current knowledge base about hydrological response to climate change. Additionally, the results also reveal important implications for water resources management and climate change adaptation.

2.5.1. Comparison: impact signal and improvements in uncertainties

Our results further confirm and solidify the Mekong's hydrological intensification in response to climate change (Sections 2.4.3 and 2.4.4). In general, hydrological impact signals from the CMIP5 scenarios are in line with findings from most previous CMIP3-based studies. This study projects an increase of +5% in average annual river discharge at Kratie, compared to +10, +4, and +3% by Hoanh et al. (2010), Västilä et al. (2010), and Lauri et al. (2012), respectively. Similar to these studies, our results also show increasing monthly and seasonal river discharges. Despite the differences in GCMs choices, climate experiment generations (i.e. CMIP5 versus CMIP3), and downscaling approaches, the increasing trend in annual and seasonal river flow is robust across different studies. Therefore, certain confidence can be placed on the general direction of the Mekong's hydrological change under climate change.

Table 2.4 Comparing projected precipitation and discharge changes across studies.

	Eastham et al. 2008	Kingston et al. 2011	Lauri et al. 2012	Thompson et al. 2013	**Hoang et al. 2016 (this study)**
Range of annual precipitation change	0.5% to 36% (A1B)	-3% to 10% (2°C warming)	1.2% to 5.8% (B1) -2.5% to 8.6% (A1B)	-3% to 12.2% (2°C warming)	**3% to 4% (RCP4.5)** **-3% to 5% (RCP8.5)**
Scenarios projecting higher annual precipitation	Not available	4 out of 7	9 out of 10	4 out of 7	**9 out of 10**
Range of annual discharge change	Not available	-17.8% to 6.5% (at Pakse, 2°C warming)	-6.9% to 8.1 % (B1) -10.6% to 13.4% (A1B)	-14.7% to 8.2% (2°C warming)	**3% to 8% (RCP4.5)** **-7% to 11% (RCP8.5)**
Scenarios projecting higher annual discharge	Majority of GCMs show increasing trend	3 out of 7	7 out of 10	3 out of 7	**9 out of 10**

Furthermore, the projected impact signals in this study exhibit less uncertainty compared to similar CMIP3-based assessments. A cross-study comparison (see Table 2.4) forthe representative Kratie station shows that both the impact signal's range and cross-scenarios agreement on directional changes improved markedly in this CMIP5-based study. In particular, the ranges of annual discharge change, i.e. 3 to 8% (RCP4.5) and -7 to 11% (RCP8.5), are typically smaller than those projected by earlier studies including Eastham et al. (2008), Kingston et al. (2011), Lauri et al. (2012) and Thompson et al. (2013). Similarly, the projected precipitation changes also show less uncertainty in the CMIP5 scenarios compared to the CMIP3 scenarios. Additionally, directional discharge changes also show better consensus in this study. The CMIP5-based ensemble's impact signal (i.e. increasing annual discharge) is supported by 9 out of 10 individual scenarios, whereas other studies show relatively lower consensus. Lastly, we compared uncertainty in hydrological extremes by calculating the coefficient of variation for projected yearly peak discharges between studies. Due to limited data availability, we only compared our study with Lauri et al. (2012). Both studies have ensembles of 10 projections, grouped into a mid-range scenario (i.e. RCP4.5 versus SRES-B1) and a high scenario (i.e. RCP8.5 versus SRESA1B). Overall, our CMIP5-based projection exhibits lower uncertainty, shown by lower coefficients of variation for both the mid-range scenarios (24% vs. 38 %) and the high scenario (25% vs. 38 %). Reduced uncertainty detected in our study is also in line with studies by Sperber et al. (2013) and Hasson et al. (2016), where they found improved representations of the Asian summer monsoon with the CMIP5 models.

2.5.2. Implications for water management

Projected hydrological changes, especially increases in high flow and low-flow conditions under climate change show important implications for water management in the river basin. First, higher peak discharges occurring at higher frequencies during the wet season will increase the flood risks across the basin. Higher flood risks will be particularly relevant for human safety and agricultural production in the lower Mekong region, including the Cambodian and Vietnamese delta. Vast agriculture areas along the main rivers and in the delta's floodplain will likely experience higher flood water levels, thus having higher risks of reduced productivity and crop failure. Higher river flow, combined with sea level rise will also result in higher flood risks for urban areas in the Mekong Delta.

Second, increased water availability during the dry season suggested by the Q95 and discharge deficit analyses can have positive implications. The projected higher river discharge during the dry season months could help to mitigate water shortage in the basin. Higher dry season flow will also contribute to control saltwater intrusion in the Vietnamese Mekong delta, where fresh water flow from upstream is currently used to control the salt gradient in rivers and canals in the coastal area. Additionally, projected discharge reduction at the beginning of the wet season (i.e. in June) probably has negative impacts on ecological and agricultural productivity. Flow alteration in the early wet season will likely change the sediment and nutrient dynamics in the downstream floodplains, which are very important for existing ecosystems and agricultural practices (Arias et al. 2012). Lastly, rainfall reduction in some areas of the lower Mekong could damage agricultural production, especially rainfed agriculture.

2.5.3. Limitations and way forward

We acknowledge several limitations and potential sources of error in this research. First, combining two historic climate data sets (i.e. the WATCH and the APHRODITE) may introduce errors due to inconsistencies. However, our data set selection is motivated by careful consideration of data quality and availability. Although APHRODITE provides high quality precipitation data (Vu et al. 2012; Lauri et al. 2014), this data set lacks temperature data needed for the hydrological model. We therefore supplement temperature data from the commonly used WATCH Forcing Data. Furthermore, calibration and validation results show that our hydrological simulation based on the combined climate forcing data is able to realistically reproduce historic river discharge. Given relatively lower modelling skill at Chiang Saen, interpreting the hydrological impact signal at this station requires extra caution. Combinations of temperature and precipitation data sets were also shown by Lauri et al. (2014) to yield sufficient accuracy in hydrological modelling in the Mekong basin. Second, this paper only uses one bias-correction method (i.e. Piani et al. 2010) for climate data preparation. This could affect the derived hydrological impact signal (Hagemann et al. 2011) but is unlikely to change the main signal of hydrological change. Additionally, including other bias correction methods is outside this paper's scope given our primary interest to understand how the Mekong's hydrology will change under climate change. Third, due to limited data availability, we could not include climate change projections from regional climate models (e.g. CORDEX) in our study. Such inclusion of such high-resolution climate projections could be useful, not only for this study, but also for the current knowledge base about the Mekong's hydrology under climate change. The scope of this study is to understand how climate change will affect Mekong's hydrology including extremes. Hydrological changes, however, are simultaneously driven by multiple factors including irrigated land expansion, urbanization, hydropower dams, and inter-basin water transfer. For example, several studies, including Lauri et al. (2012), Piman et al. (2013), and MRC (2011a), have shown that irrigation expansion, hydropower dam construction, and water transfer projects can largely alter flow regime. Such anthropogenic factors should be subjected to future studies in order to yield more comprehensive insights about the Mekong's future hydrology and water resources. Of special importance in this regard is the need to assess the interactions between different drivers and the resulted hydrological changes.

2.6. Conclusions

This study is one of the first hydrological impact assessments for the Mekong River basin focusing on hydrological extremes under climate change. We aim to cover this particularly important knowledge gap, and thereby better supporting policy and decision making in Southeast Asia's largest river basin.

Climate change scenarios show that temperature consistently increases across the basin, with higher rises in the upper basin in China, large parts of Thailand and the Vietnamese Mekong delta. Basin-wide precipitation also increases under a majority of scenarios (9 out of 10), but certain areas also exhibit reducing signal. As a result, the Mekong's hydrology will intensify, characterized by increases in annual river discharge at all stations. The scenario ensemble means also show increases in seasonal discharges, for both wet and dry seasons. Discharge increases are more substantial during the wet season, but the ensemble ranges are more variable compared to the dry season. Considerably different and sometimes contrasting directional discharge changes exist in our scenarios ensemble. This uncertainty, although reduced markedly compared to earlier CMIP3-based assessments, highlights a challenge in quantifying future hydrological change. It emphasizes the importance of, first, using ensemble approach in hydrological assessments, and second developing robust, adaptive approaches to water management under climate change.

Lastly, we found substantial changes in hydrological extremes concerning both low-flow and high-flow conditions. Water availability during dry season increases under all climate change scenarios, suggesting positive impacts on water supply and salinization control in the downstream delta. Wet season discharges and annual peak flows will increase substantially, implying important consequences for risk management, especially in securing safety of water infrastructures, and in controlling flood risks in the Mekong Delta. Given robust evidences of changes in hydrological extremes, shifting research and management focuses to these low-probability but potentially highly damaging events is important to reduce climate change impacts and associated risks.

The Supplement (Supplementary information A and B in this thesis) related to this article are also available online at doi:10.5194/hess-20-3027-2016-supplement.

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CHAPTER 3

The Mekong's future flows under multiple stressors: How climate change, hydropower developments and irrigation expansions will drive hydrological changes?

Abstract

The Mekong River's flow regime and water resources are in many ways essential for economic growths, flood security for about 70 million people, and ecosystem dynamics in the world's 2nd most biodiverse wetland. This flow regime, although remains relatively unregulated, is expected to be increasingly perturbed by climate change and rapidly accelerating socioeconomic developments. Current understanding about hydrological changes under the combined impacts of these drivers, however, remains limited. This study presents projected hydrological changes caused by multiple drivers, namely climate change, large-scale hydropower developments, and irrigated land expansions for the 2050s. We found that the Mekong's future flow regime is highly susceptible to all considered drivers, shown by substantial changes in both total flows (annual and monthly) and in the seasonal flow distribution. While hydropower developments exhibit limited impacts on annual flows, climate change and irrigation expansions results in changes of +15% and -3% in annual flows, respectively. However, hydropower developments exhibit the largest seasonal impacts characterized by higher dry season flows (up to +70%) and lower wet season flows (about -15%). These strong seasonal impacts tend to outplay those of the other drivers, resulting in the overall hydrological change pattern as strong increases of the dry season flow (up to +160%); flow reduction in the first half of the wet season (up to -25%); and slight flow increase in the second half of the wet season (up to 40%). Next to changes in the flow seasonality, cumulative impacts of all drivers result in substantial flow reductions (up to -25% in July) during the early wet season. Flow reductions during this critical period will directly affect crop production and saltwater intrusion in the downstream delta, which depends greatly on increasing river flows after the dry months. Substantial flow changes and their likely serious consequences call for, first, careful considerations of future developments and second, effective adaptation and preparedness to future changes.

The manuscript corresponding to this chapter is currently under preparation for journal submission.

3.1. Introduction

The Mekong is the largest and most important transboundary river basin in Southeast Asia. The river starts in China and flows across Myanmar, Laos, Thailand, Cambodia, down to its endpoint in the East Sea (also known as South China Sea) in Vietnam. The societies and economies along the river are highly dependent on the commonly shared water resource, especially in the agriculture, fisheries and energy sectors (Hortle, 2007a; Grumbine and Xu, 2011; Arias et al. 2014). A large share of the population (currently 70 million, based on Varis et al. 2012) including millions of farmers in Cambodia, Laos, and the Vietnamese Mekong Delta have their livelihoods directly supported by the water resources from the river. Abundant water resources and a strong seasonal flood pulse also create the largest wetland (i.e. Lake Tonle Sap) in Southeast Asia. This wetland system exhibits important ecological values (Arias et al 2014; Lamberts and Koponen, 2008) and contributes to about 80% of the protein supply for millions of local inhabitants (Hortle, 2007b). The Mekong also features high potentials for hydropower production, of which only a small proportion (i.e. about 10%) is currently exploited (MRC, 2010). Hydropower production generated about USD $250 million per year (MRC, 2005) and contribute substantially to regional economic developments. All these great benefits and high dependencies highlight the importance of the Mekong's water for local livelihoods and regional economic developments.

Nevertheless, the Mekong's flow regime and water resources are expected to experience substantial changes due to multiple factors including climate change, hydropower developments and irrigated land expansions. Recent studies including Eastham et al. (2008), Västilä et al. (2010), Lauri et al. (2012) and Hoang et al. (2016) suggest that climate change will likely change the Mekong's flow regime, resulting in higher magnitudes and frequencies of floods and droughts. Seasonal flows are also projected to change under future hydropower developments throughout the basin (Lauri et al. 2012, Piman et al. 2013). Also, rapid irrigated land expansions are projected for the Mekong, which could result in almost doubling the total irrigated area within the coming two decades (MRC, 2010). Irrigated land expansions will result in increasing irrigation demands and will likely affect the Mekong's flows, especially during the dry season (Piman et al. 2013). Although existing studies provide useful insights about the impacts of individual factors, much less attention is paid to the combined impacts of multiple factors on the Mekong's future flows. Given the potentially large, sometimes contrasting impacts of each factor, understanding future hydrological changes caused by multiple driving factors is highly important to effectively inform and support long-term planning and decision making in the Mekong basin.

Against this background, the main objective of this study is to characterize and quantify the impacts of multiple factors, including (1) climate change, (2) hydropower dam developments and (3) irrigated land expansions on the Mekong's future flow regime. For such objective, we developed a coupled modelling system including a dams operation module and a crop simulation module into a distributed hydrological model, allowing for simultaneous simulation of the three factors. Furthermore, we prepared multiple scenarios to characterize future changes for each factor for 2050s. Simulation results under these scenarios are presented to provide insights about how river flows at representative locations will change due to the considered driving factors.

3.2. The Mekong River basin

The Mekong (Figure 3.1) is an average-sized river basin compared to other major rivers of the world. The river's total length and total catchment area are 4800 km and 795 000 km^2, respectively. However, the Mekong's total annual discharge volume (i.e. 475 km^3 per year) is much higher than other similarly-sized river basins, making it the 10^{th} largest river in this regard (Dai and Trenberth, 2002). High discharge volume is mainly attributed to the monsoonal activities, most importantly the south-west monsoon (MRC, 2005; Delgado et al. 2012). The tropical monsoonal climate results in two distinctive wet (May-October) and dry seasons (November-April), with over 75% of the total discharge generated during the wet season (MRC, 2009a). The monthly flow regimes at key stations along the Mekong are presented in Figure 3.3-a. During the flood season, large floodplains are flooded annually in the Mekong downstream countries, especially in Cambodia and Vietnam. The annual flood pulse and nutrient-rich floodwater supports high aquatic biodiversity, rich fisheries and a highly productive rice production system. Extreme floods, however, cause live losses and large damages to crops and infrastructure, thus constitute a major safety risk in the downstream delta.

Riparian countries along the Mekong are experiencing rapid socio-economic developments. Population is increasing steadily and this trend is projected to continue in the coming decades (Varis et al. 2012). Irrigated land expansions are increasing throughout different parts of the basin and recent studies also project drastic future increases in irrigated land in the Mekong (Eastham et al. 2008; MRC, 2010). Similarly, energy supply, mostly through hydropower developments is accelerating throughout the basin (Orr et al. 2012; Grumbine and Xu, 2011). These rapid developments will increase Mekong's water resources utilisation and subsequently modify the river's current flow regime. On top of socio-economic development, climate change is projected to have substantial impacts on river flows (Lauri et al. 2012; Hoang et al. 2016). All in all, flow regime changes caused by climate change and human activities will pose great challenges for socio-economic developments, especially for agriculture, fishery, water resources management and ecosystem dynamics. Therefore, quantifying the Mekong's future flow regime changes and characterizing the underlying mechanisms are especially important.

3.3. Climate change, irrigation expansion and hydropower development scenarios

3.3.1. Climate change

Baseline climate data were prepared from the WATCH forcing data (Weedon et al., 2011) and the APHRODITE data set (Yatagai et al., 2012) for four required variables, namely daily mean, maximum and minimum temperatures, and precipitations. Climate change scenarios were prepared using climate projections from the Coupled Model Intercomparison Project 5 (CMIP5) for five GCMs and two RCPs (i.e. RCP4.5 and RCP8.5) for the 2036-2065 period. Based on on several model evaluations by Huang et al. (2014), Hasson et al. (2016), and Sillmann et al. (2013), we included five GCMs in this study, namely ACCESS-1.0 (ACCESS); CCSM4 (CCSM); CSIRO-Mk3.6.0 (CSIRO); HadGEM2-ES (HadGEM); and MPI-ESM-LR (MPI). Furthermore, the GCM data were downscaled and statistically bias corrected following Piani et al. (2010). For more details on GCM selections and data preparation see Hoang et al. (2016).

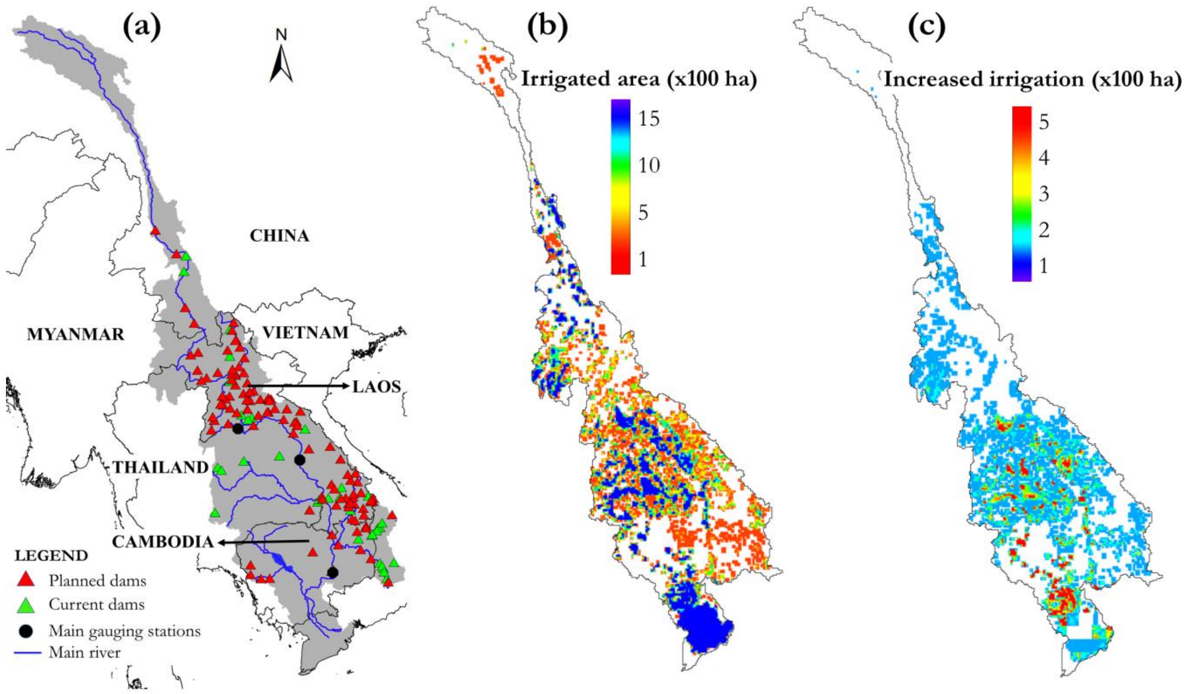

Figure 3.1 Scenarios of future hydropower developments and irrigated land expansions in the Mekong basin: (a) Existing and future hydropower dams; (b) Irrigated rice area per 5 km x 5 km gird under baseline situation for the first cropping season; (c) Projected increases in irrigated rice area under high expansion scenario

3.3.2. Hydropower development scenarios

We prepared a hydropower development scenario based in the hydropower dam database provided by the Mekong River Commission (MRC, 2009b) and the hydropower dam data from ADB (2004). In total, our hydropower development scenario includes 126 dams on both mainstreams (N=16) and tributaries (N=110) of the Mekong, equivalent to a total active storage of 108 km^3. Currently, a majority of these dams are under construction or in planning phase (see Figure 3.1-a) and all dams will turn fully operational by the 2036-2065 period.

3.3.3. Irrigation scenarios

For irrigation, we prepared a baseline scenario using data from the MIRCA - "Global Dataset of Monthly Irrigated and Rain-fed Crop Areas around the Year 2000" (Portmann et al. 2010). The MIRCA data set provides data on irrigated area and cropping calendar for 26 different crops at 5 arc-minutes resolution, equivalent to about 9 km x 9 km at the Equator. We resampled the MIRCA data and created a new irrigation raster layer with the resolution of 5 km x 5 km to keep consistent to the VMod model's grid. Since irrigated rice is the most dominant crop in the Mekong basin (account for over 80% of the total irrigated land) we focus on irrigated rice in our irrigation scenarios. For baseline, the total irrigated rice area in the Mekong is 4.1 million ha, attributed to two cropping seasons. Of this total sum, about 2.04 million ha is cultivated in the first growing season (starting in May) and the other 2.07 million ha belong to the second growing season (starting in October). Lastly, we developed two irrigation scenarios using the MIRCA and the global projected irrigation expansion scenarios by Fischer et al. (2007). We applied spatially explicit irrigated land expansion factors derived from Fischer et al. (2007) on the baseline MIRCA data to calculate future irrigated area for rice crop (Figure 3.1-c).

3.4. Modelling setups

3.4.1. VMod hydrological model

We used a distributed hydrological model – the VMod (Lauri et al. 2006) to simulate the Mekong's hydrology. The hydrological model was selected based on demonstrated good performance in the Mekong (Lauri et al. 2012, Räsänen et al. 2012, Darby et al. 2016, Hoang et al. 2016). Hydrological simulations are done per grid cell, starting from calculating climate forcing from the input climate data, followed by simulating soil surface processes and the soil's water balance. After these steps, calculated runoff water from each grid cell will be routed through the river network using a standard routing scheme. In this study, we used the modelling setup for the Mekong developed by Lauri et al. (2012) and Hoang et al. (2016). This setup covers the whole river basin and allows for daily hydrological simulations at a 5 km x 5 km spatial resolution. The VMod's technical descriptions are available in Lauri et al. (2006) while more detailed information about the model set up for the Mekong basin is provided in Hoang et al. (2016).

3.4.2. Hydropower dam operation module

Since data about hydropower dam operation are not available, we simulated the dam operation rules by simulating monthly outflow for each dam. Dams simulation was based on the optimisation scheme developed by Lauri et al. (2012), which aims to maximize productive outflows (i.e. outflows through the turbines), thus maximising hydropower production. The optimisation scheme uses a set of parameters, namely active storage, monthly inflow, minimum outflow and designed optimal outflow to calculate the monthly outflows for each individual dam. Several additional constrains are also added to the dams' operation, including keeping dry season flow constant; and reservoirs filling and emptying during the wet season and dry season, respectively. Operation rules were developed for each individual dam, following a upstream-to-downstream sequence. As such, operations of the downstream dams were simulated taking into account flow regulation effects caused by upstream dams. Technical description for the hydropower dam operation module is available in Supplementary Information C.

3.4.3. Crop and irrigation module

To simulate irrigation impact on flow regime, we developed a crop and irrigation water use module based on the AquaCrop model (FAO, 2012). Following the AquaCrop's approach, the developed crop and irrigation module simulates crop growth through a step-wise procedure, starting from calculating the soil water balance, followed by canopy developments, crop water use, irrigation demand, biomass and crop yields. The crop irrigation demand for rice crop is calculated as sum of three components. The first component accounts for the amount of water to saturate rice fields at the beginning of the cropping season i.e., to bring soil water up to field capacity. The second component accounts for the amount of water to flood the fields i.e., rice ponding during the cropping period. The ponding water levels are maintained within a range of 75 to 150 mm, which was derived based on field observations. Water levels in the rice field are controlled by compensating for water losses caused crop evapotranspiration and, to a lesser extent, infiltration to deeper soil layers. The required water for maintaining the ponding water levels constitutes the third component of the gross irrigation demand. Technical description for the crop and irrigation module is available in Supplementary Information D.

We aim to quantify an upper limit for rice irrigation water demand and thus designed the irrigation scheme to provide optimal water supply for rice crop. Irrigation starts when ponding water level drops below the lower limit (i.e. below 75 mm) and stops when water level exceeds the upper limit (i.e. 150 mm). Given limited use of groundwater irrigation in the Mekong basin, we assume that all irrigation water is withdrawn from surface water via extraction points locating along the river network.

3.4.4. Model calibrations, validations and modelling setups

The hydrological module in VMod was calibrated and validated for seven mainstream stations (i.e. Chiang Saen, Luang Prabang, Nong Khai, Nakhom Phanom, Pakse, Stung Treng, and Kratie) by Hoang et al. (2016). Calibration and validation results during 1981-2001 show good performance in reproducing historic discharges of the Mekong, with reported better skills in the more downstream stations. The hydropower dams optimisation module was developed for the Mekong by Lauri et al. (2012). This module's performance was then assessed against the observed impacts of the Chinese dam cascade, showing realistically simulated seasonal impacts by by Räsänen et al (in press).

Table 3.1 Model runs and scenario setups

Model runs	Baseline scenario	Future scenario
Climate change impact	Baseline climate	Future climate (RCP4.5 & RCP8.5)
Hydropower development impact	Baseline climate Inactive dams	Baseline climate Active dams
Irrigation expansion impact	Baseline climate Baseline irrigation	Baseline climate Future irrigation (IRR_Low & IRR_High)
Combined impact of three drivers	Baseline climate Inactive dams Baseline irrigation	S1: RCP4.5 + IRR_Low + Dam S2: RCP4.5 + IRR_High + Dam S3: RCP8.5 + IRR_Low + Dam S4: RCP8.5 + IRR_High + Dam

The Aquacrop-based crop simulation module was developed and validated following a two-step procedure. First, the crop simulation module was tested by comparing simulated crop outputs with reference data from the Aquacrop model (World Bank, 2012). Comparison results for several output parameters (canopy cover, crop biomass and crop yield) for multiple crops including wet rice show good agreements between the crop module and Aquacrop. In the next step, simulated yields, crop water use and irrigation water demand for wet rice were calibrated in two sub-catchments, namely the Xebang Fai sub-catchment in Laos (World Bank, 2012) and the Yom sub-catchment in Northern Thailand (ICEM, 2015).

We aimed to quantify future flow regime changes caused individually be each driver and cumulatively by all three drivers. For this purpose, we designed five groups of model runs, each run consists of a baseline and a future scenario (Table 3.1).

3.5. Results

3.5.1. Impacts of individual drivers on flow regime

Flow changes under sole climate change

Our climate change scenario ensemble shows consistent temperature increase of between +1.9°C (RCP4.5) and +2.4°C (RCP8.5) in the Mekong basin. Basin-wide precipitation is also projected to increase under a majority of ensemble members (i.e. 9 out of 10), showing changes of between -3% (HadGEM-RCP8.5) to +5% (CCSM-RCP8.5). Temperature and precipitation changes are projected to intensify the Mekong's hydrological cycle, resulting in substantial increases in both annual and seasonal flows (Figure 3.2-a). Annual flows at the most downstream station in Kratie change between -7 and +11%, with only one scenario member (i.e. the HadGEM-RCP85) showing flow reductions. Dry season flows increase substantially, especially during the January-May period. Flow increases during these months range between +15% to +20%, with higher increases for more upstream stations in Vientiane and Mukdahan. Wet season flows also show a similar increasing trend, however, relative changes are smaller compared to the dry season. Additionally, monthly flow changes exhibit contrasting signal between the early wet season months (i.e. June-July) and the rest of the wet season. The scenario ensemble projects no change to reductions of up to -7% during June-July, with more substantial reductions at the lower Kratie station. The peak flow period (August-September) show flow increases of +5% to +8% at Vientiane, and of +3% to +8% at Kratie. For more details on climate change impacts on flow regimes and hydrological extremes, see Hoang et al. (2016).

Flow changes under sole hydropower dam developments

Simulation results show substantial flow alterations caused by hydropower dam developments along the Mekong. Although annual river discharge remains more or less the same compared to the dams-free scenario, monthly and seasonal flows are largely modified by the dams (Figure 3.2-b). Overall, dams operation leads to substantial increase in the dry season flows whereas wet season flows is reduced. Flow modification patterns under hydropower dam scenarios are consistent for all considered stations, only with variations in the magnitudes. Dry season flows increase between +63% Kratie and +70% at Mukdahan, with the highest monthly increase in April (up to +133% at Kratie Station). On the other hand, wet season flows show smaller, yet still noticeable, reductions between –15% (at Kratie and Vientiane) and –16% (at Mukdahan). Flow reductions during the wet season are most substantial during the first half of the wet season (i.e. June-September) and the flows start to increase again by November.

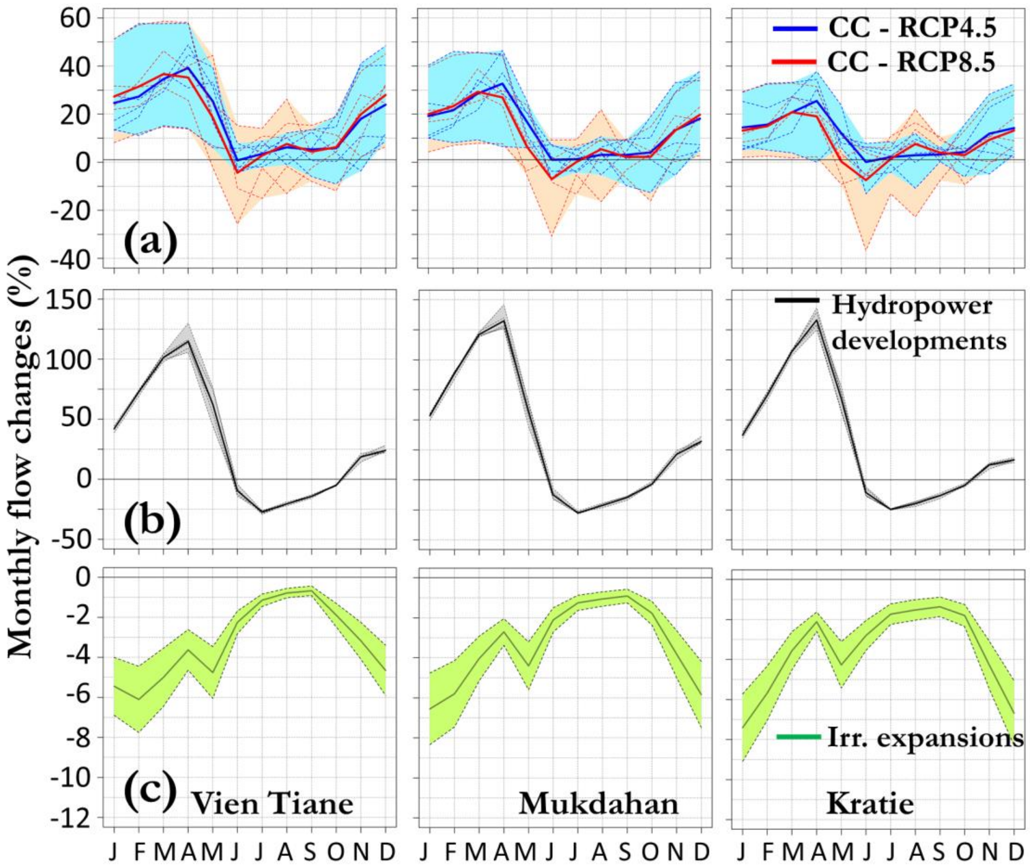

Figure 3.2 Projected monthly flow changes at three main stations (Vientiane, Mukdahan and Kratie) under sole impacts of individual drivers: (a) climate change; (b) hydropower developments; and (c) irrigated land expansion for the 2050s period

Flow changes under sole irrigated land expansions

Total irrigated rice area is projected to increase from 4 million ha to 5.4 and 5.8 million ha under the moderate and high expansion scenarios, respectively. The projected total irrigated rice areas under two scenarios are well in line with the MRC's projections. According to the MRC's scenarios, total irrigated rice area will reach 5.1 and 5.8 million ha under the "20-year development" and "Long-term development" scenarios, respectively (MRC, 2010). Regarding spatial distribution, irrigated rice is projected to expand mostly in the lower Mekong countries including South-Western Thailand and Southern Cambodia where there are still potential for agricultural expansions. The upper Mekong, on the other hand, shows limited expansion due to limited land available for agricultural expansion.

As results of future irrigated rice expansions, river flows show consistent reductions at all considered stations (Figure 3.2-c). Annual flows at Vientiane are projected to reduce between -1.4% to -2.4% under the moderate and high expansion scenarios, respectively. Flow reductions tend to increase further downstream, shown by annual reductions of up to -3.2% at Kratie station under the high expansion scenario. Furthermore, monthly flow reductions show some variations throughout the year. Relative flow reductions during the dry season months (i.e. January-May) are more substantial compared to those in the wet season months (i.e. July-September). While dry season flows show reductions of up to -9% (January at Kratie) for high expansion scenario, smaller relative changes (typically -1% to -2%) are projected during the wet season months.

3.5.2. Combined impacts of three drivers on flow regime

The Mekong's monthly flow regimes show substantial changes under the combined impacts of climate change, hydropower developments and irrigation expansions. Flow changes at all considered stations share relatively similar patterns, characterised by contrasting impact signal between the wet and dry seasons (Figure 3.3-a and 3.3-b). Dry season flows exhibit consistent increases, with markedly larger magnitudes in March and April. During this period, monthly flows at Vientiane increase by about +125% while downstream stations at Mukdahan and Kratie show relatively higher increases of up to +150%. In contrast to the increasing trend during the dry season, wet season flows show an overall decreasing trend at all stations. The flow changes' magnitudes, however, are markedly smaller compared to those of the dry season. Flow starts to decrease in June (typically around -10%) and reached the largest reduction of about -25% in July. After this, flow reductions progressively diminished over time and by the end of the wet season (i.e. October) monthly flows reach the same levels as those under the baseline situation, i.e. relative changes around 0% for all stations.

Regarding hydrological extremes, high and low river flows generally show similar changing patterns as monthly flow changes (Figure 3.4). The probability exceedance curves show substantial increases in the annual minimum river flows under future scenarios for all considered stations (Figure 3.4 – lower panel). Contrary to low flow changes, simulated annual peak flows show overall flow reductions. The more extreme high flows (i.e. exceedance probability lower than 0.4), however, show remarkable increases for the most upstream Vientiane station. Peak flow increases at Vientiane is explained by strong flow increases caused by climate change and relatively smaller flow regulation impacts of upstream hydropower dams. The probability exceedance curves at Mukdahan and Kratie stations also show that despite the overall reducing trends, very extreme high flows (i.e. exceedance probability lower than 0.2) tend to reduce less substantially compared to more moderate annual peak flows.

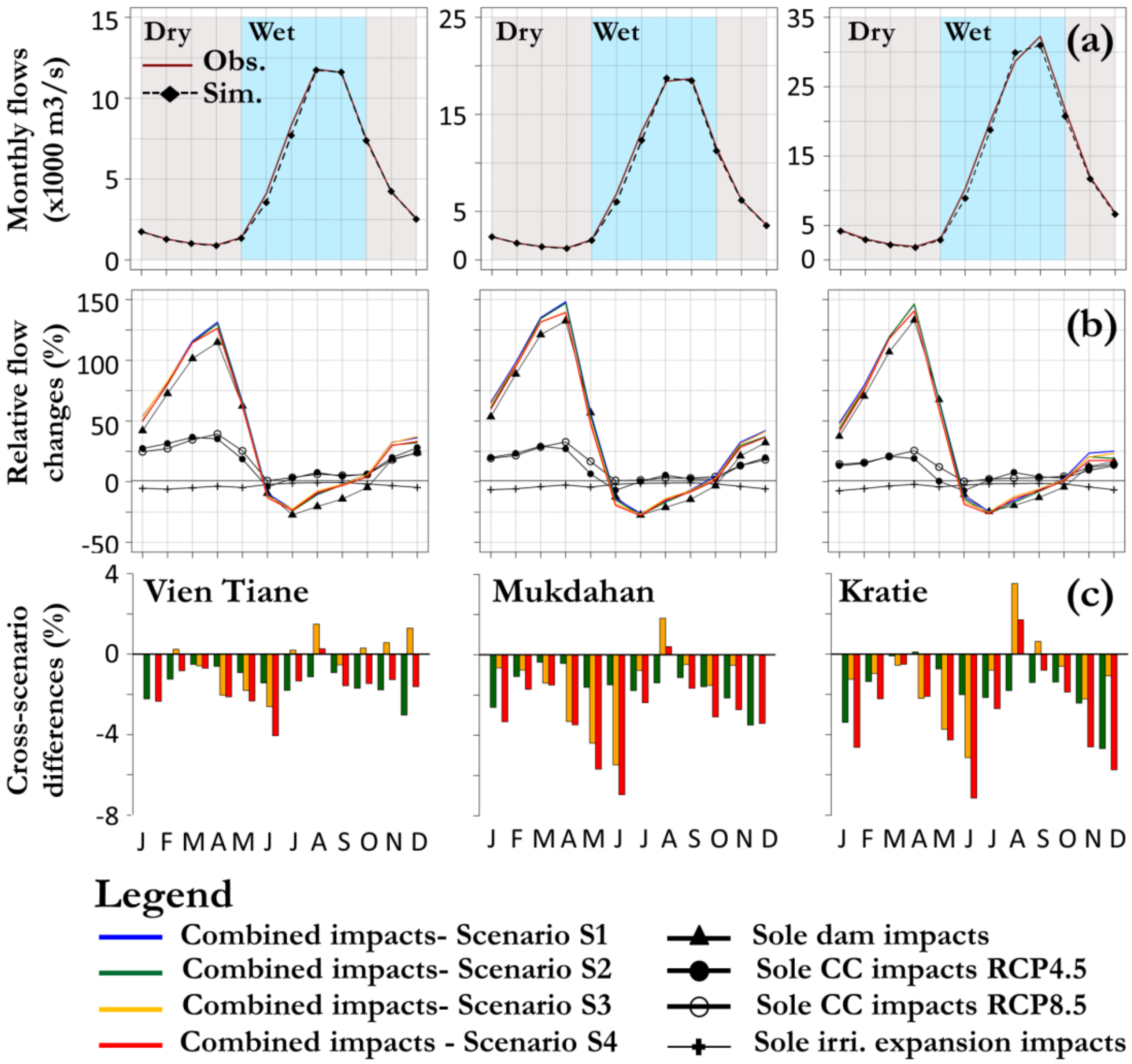

Figure 3.3 Baseline monthly flows at Vientiane, Mukdahan and Kratie (a); Projected flow changes (%) under four (S1-S4) multiple-driver scenarios, i.e. coloured lines/bars (b); Cross-scenario relative differences compared to S1 (c). Full descriptions for scenarios S1-S4 are provided in Table 3.1.

Notably, the flow-change patterns are somewhat similar across the four considered future scenarios (i.e. S1-S4). Some cross-scenario differences, although are relatively marginal in comparison to the cross-driver differences, are remarkable during the March-April, June, and November-December periods. Flow changes during March-April under the RCP8.5 scenario, i.e. the S3 and S4, are smaller than those under the RCP4.5 scenario, i.e. the S1 and S2 (Figure 3.3-c). Cross-scenario differences are also noticeable during the November-December period, where the scenarios featuring the higher irrigation expansion scenario (i.e. S2 and S4) show less flow increases compared to those featuring lower irrigation expansion scenario (i.e. S1 and S3). Additionally, the flow changes under the three drivers largely share the same patterns with that of the hydropower dam driver.

The magnitudes of changes, however, show considerable modifications to the sole hydropower development impacts. For example, flow increases during March and April are typically +20 to +25% higher under the combined scenarios compared to the sole hydropower developments impacts.

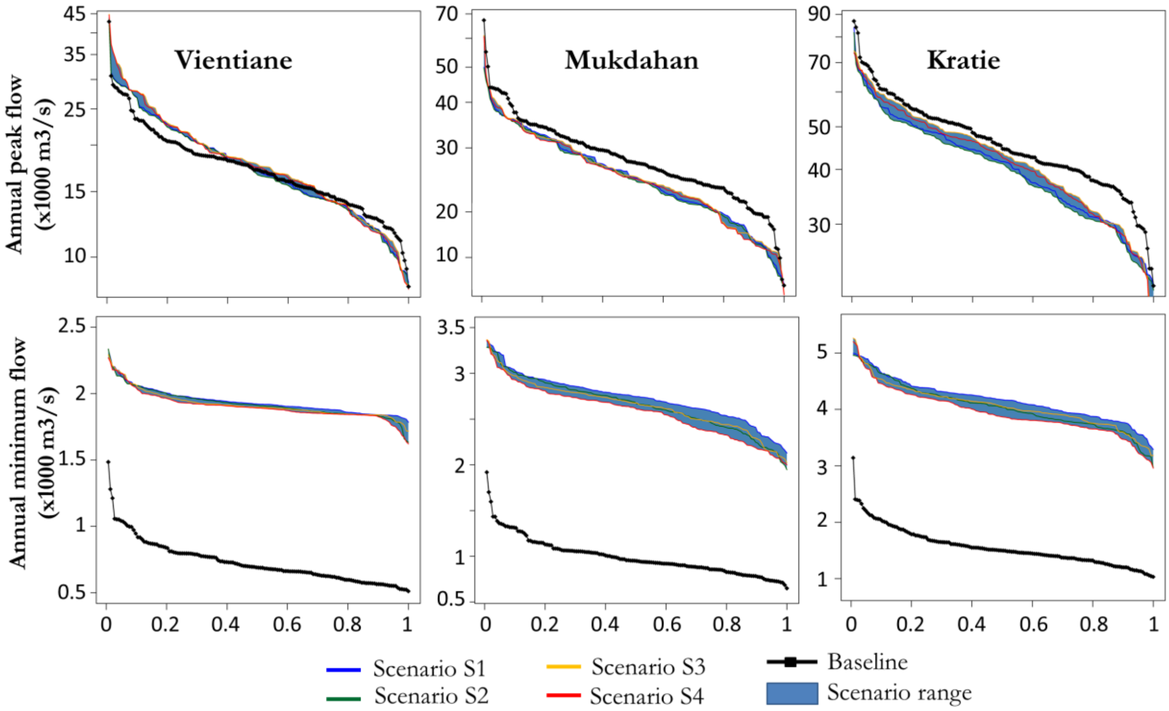

Figure 3.4 Exceedance curves of annual peak flows (upper panel) and annual minimum flow (lower panel) at main stations under multiple drivers' impacts. Note the log-scale applied to the y-axis of the plots in the upper panel. Full descriptions for scenarios S1-S4 are provided in Table 3.1.

3.6. Discussion

Main findings

Substantial flow changes show that the Mekong River's flow regime is susceptible to large and abrupt changes due to climate change and development activities. Flow changes are substantial, both under the individual driver impacts and under the combined impacts of multiple drivers. The projected flow increases under climate change further strengthen the current knowledge body about the Mekong's flow responses to climatic stimuli. This finding is in line with a majority of earlier studies including Eastham et al. (2008), Kingston et al. (2011) and Lauri et al. (2012). Additionally, the climate change impact signals from this study exhibit lower uncertainty, characterized by smaller ensemble range and higher cross-scenario consensus over the directions of flow changes. Regarding hydropower developments, our results show strong modifications to the flow's seasonality, characterized by increasing river flow during the dry season and reducing flow during the wet season. This flow alteration pattern by the dams is in line with earlier studies including ADB (2004), Lauri et al. (2012) and Piman et al. (2013). This cross-study similarity is partly due to the fact that all studies used more or less the same hydropower development scenario from the Mekong River Commission (MRC, 2009b). Our results, however, show considerably higher flow increases during the dry season (i.e. around 60%) compared to a projected increase of 29% by Piman et al. (2013). More moderate flow changes found in Piman et al. (2013) could be due to the fact that the authors combine the dams' impacts with those of water withdrawals for irrigation and other uses. These withdrawals, which result in flow reductions, partly compensate for the flow increases caused by the dams. Regarding impacts of irrigation expansions on river flows, our results show overall flow reductions throughout the year, with monthly values ranging between -1% to -9% depending on the season and irrigation scenario. Unfortunately, comparing our irrigation assessment results with other studies was not possible due to unavailable data.

Flow changes under the multiple driver simulations reflect the accumulated impacts of the individual drivers. These accumulations are characterized by both impact exacerbations and compensations, resulting in flow changes that tend to differ from those caused by the individual drivers, especially for the climate change and irrigation expansion drivers. This notion highlights the importance of integrated impact assessments which allow for proper considerations of the impacts of multiple drivers on the Mekong's flows. Impact exacerbations occur during the early wet season and the entire dry season. The early wet season (i.e. June-July) exhibits the largest flow reduction throughout the year, which is the result of accumulated flow reductions caused by all drivers. Similarly, higher river flows during the dry season are resulted from the combined impacts of precipitation increases and hydropower dam operations. Impact compensations are mostly visible during the August-October period, when flow increases caused by climate change compensate for a considerable portion of the flow reductions caused by hydropower dams and irrigation withdrawals. Furthermore, although flow regime changes reflect the accumulated impacts of the three considered drivers, these changes are to a large extent dominated by hydropower developments. This shows that hydropower dams are the most predominant driver of future hydrological changes within the timeframe of this study (i.e. 2050s), being in line with Keskinen et al. (2015). We found that hydropower developments exhibit impacts with markedly larger magnitude compared to those of climate change and irrigation expansions. These strong flow modifications by dam operations explain similar patterns between the cumulative impacts and the sole dams' impacts.

Potential implications of flow regime changes

Substantial changes in the Mekong's flow regime will likely have important implications for agricultural production, water management and ecosystem dynamics. General flow increases in the dry season could have positive impacts on crop production and saltwater intrusion management in the Vietnamese Mekong Delta. Higher water availability during the dry season months (i.e. January-April) could effectively help to overcome water shortage, which is a key limiting factor for agricultural production in the Mekong region (Son et al. 2012). Additionally, higher dry season flows will also allow for better control of saltwater intrusion in the downstream Mekong Delta (MRC, 2005; Smajgl et al. 2015). Sufficient upstream inflows will help mitigating high salt concentration in the river branches and open channels during low flow events, thereby preventing damages for crops and sustaining water supplies. Furthermore, lower wet season flows imply lower flood risks along the main rivers, especially in the main floodplains in Cambodia and Vietnam.

Projected changes in the Mekong's flow regime will also likely result in many negative consequences. Firstly, large alterations to the natural flow regime will create disturbances to the aquatic ecosystems though changing the natural habitats of native species, distribution of vegetation, and fish migrations (Arias et al. 2012; Kummu & Sarkkula, 2008). Reduced river flows during the wet season may impede the natural sedimentation process caused by overland water flows in floodplains. Reduced sedimentations will affect crop yields, which largely benefits from the rich nutrients carried by the sediment during flood events. Additionally, reducing sedimentation due to dam trapping (Kummu et al. 2010 ; Kondolf et al. 2014) and decrease of tropical cyclone activity (Darby et al. 2016) will also result in higher risks of river bank and coastal erosions and land subsidence in the low-lying Mekong Delta (Manh et al. 2015).

Limitations and perspectives for future research

The integrated impact assessment in this study considered three main driving factors of flow regime changes, based on rather straightforward driver dynamics represented by the set of scenarios. Adding more driving factors and further detailing their dynamics would be meaningful to increase comprehensiveness and accuracy of the results. For example, increasing water extractions by domestic and industrial sectors may have important impacts on flow regime and thus these factors should be included in future studies. Regarding the hydropower driver, we developed an optimisation scheme to operate all dams for the sole purpose of hydropower generation. It is, however, likely that some of these dams will be used for multiple purposes including water supplies, flood and drought mitigations as suggested by Giuliani et al. (2016). This notion is especially relevant in views of future population growth, urbanisation and climate change, which would likely increase the need for using dams for multiple purposes. As a result, the dams may operate differently and thus would be relevant to further investigate the likelihood of shifting operational modes and the resulting impacts on river flow. Additionally, considering flow changes during filling up periods after the dam construction phase will help to better understand temporary abrupt flow modifications. For the irrigation driver, we focused on irrigated land expansion to represent a dominant trend in agricultural developments in the Mekong region (MRC, 2010). However, future crop production could potentially take different pathways including shifting from wet rice to less water intensive crops where water availability is limited. Such shifting pathways, their implications for irrigation water demand and ultimately river flows remains important topics for future studies.

Results from this study open up some highly relevant directions for future research. First, the strong flow modification effects of hydropower dams, and the potentially serious consequences requires careful considerations of the costs and benefits of largescale hydropower developments in the Mekong region. Future hydropower dams should be subjected to detailed impact assessments, with special attention to the cumulative impacts of the whole dam system, and impact distributions across multiple sectors and regions. Flow regulation capacity of the dams also suggest the possibilities of testing the buffering capacity of hydropower dams in supporting water allocation between the wet and dry season, or in mitigating extreme floods through controlling of high flow events (Giuliani et al. 2016). Another relevant research direction could be further assessments of the impacts of future flow regime changes, for example on flood dynamics (i.e. both timing and magnitudes), fishery, agricultural production and biodiversity.

3.7. Conclusions

We implemented an integrated impact assessment to quantify and characterize future flow regime changes in the Mekong River under climate change and accelerating anthropogenic drivers, namely irrigated land expansions and hydropower developments. Results from our assessment show high susceptibility of the river's flow regime to the considered drivers and thus highlight the importance of better understanding the magnitudes and underlying mechanisms of these changes. Furthermore, our findings provide new and more comprehensive insights about future river flows alterations as results of both climate change and development activities. Such insights are of great values for supporting development planning and strategic decision making, especially in the context of rapid developments in the Mekong basin.

In essence, our main findings indicate that the Mekong will face large modifications to the monthly and seasonal flow regimes as results of future climate change, irrigation expansions and hydropower developments. While individual drivers cause substantial flow changes, largest changes are caused by the accumulative impacts of all drivers. Impact accumulations result in large flow reductions during the early wet season when river flows are especially important for crop production and for controlling saltwater intrusion in the Mekong Delta. Furthermore, the results also show that the underlying mechanisms of the flow regime changes are complex, characterised by the interplays between the impact directions and magnitudes under individual drivers. This implies that integrated impact assessments focusing on interactions between the driving factors and potential trade-offs are highly important. The projected flow changes will likely have serious implications for agriculture, fishery and ecosystems, thus calling for timely adaptation and preparedness to cope with these changes. Large impacts of hydropower dam developments and irrigation expansions call for careful considerations of future developments in order to avoid high economic and environmental costs and increased risks for the poor and the vulnerable population living in the region.

CHAPTER 4

Extreme floods in the Mekong River Delta under climate change: combined impacts of upstream hydrological changes and sea level rise

Abstract

Extreme floods cause large scale damages to human lives and infrastructure, and hamper socio-economic development in the Vietnamese Mekong River Delta. Induced by climate change, upstream hydrological changes and sea level rise are expected to further exacerbate flood hazard, thus posing critical challenges for securing safety and sustainability. Magnitude and frequency of future extreme floods, however, remain largely unknown. This paper provides a probabilistic quantification of future flood hazard for the Mekong Delta, focusing on extreme events under climate change. We developed a model chain to simulate separate and combined impacts of two drivers, namely upstream hydrological changes and sea level rise on flood magnitude and frequency. Simulation results show that upstream changes and sea level rise substantially increase flood hazard throughout the whole Mekong Delta. Due to differences in their nature, these two drivers show different features in their impacts on floods. Impacts of upstream changes are more dominant in floodplains in the upper delta, causing an increase of up to +0.80 m in flood depth. Sea level rise introduces flood hazard to currently safe areas in the middle and coastal delta zones. A 0.6 m rise in relative sea level causes an increase in flood depth up to +0.70 m by 2050s. Upstream hydrological changes and sea level rise tend to intensify each other's impacts on floods, resulting in stronger combined impacts than linearly summed impacts of each individual driver. Substantial increase of future flood hazard strongly requires better flood protection and more flood resilient development for the Mekong Delta. Findings from this study can be used as quantified physical boundary conditions to develop flood management strategies and strategic delta management plans.

The manuscript corresponding to this chapter is currently under review. An earlier version of this chapter was presented at the European Geosciences Union General Assembly (EGU), April 2016.

4.1. Introduction

The Vietnamese Mekong River Delta (hereafter, the Mekong Delta) is the most downstream sub-catchment of the Mekong – the largest river in Southeast Asia. The delta receives a great volume of water coming from upstream, averaged to 475 km^3 annually (MRC, 2005). More than 75% of this total amount is attributed to the wet season (July - December period), which is often referred to as the flood season (MRC, 2005; Le et al. 2007). Thanks to its abundant water resources, the Mekong Delta features a highly productive aquatic ecosystem and a dynamic and fast-growing economy. The delta is home to a growing population of 17.3 million people with a population density of 427 people/km^2. Economic activities, which contribute about 15% to the national GDP (MPI, 2009), are often strongly linked to the Mekong's water resources. Key water-dependent economic sectors in the delta include fishery, agriculture and aquaculture.

Annual floods are seen as a natural and beneficial phenomenon in the Mekong Delta, however extreme events often cause huge damage to human lives and infrastructure, and hinder socio-economic development (Wassmann et al. 2004; Tri et al. 2013). Moreover, the delta is now facing emerging, yet very critical challenges due to climate change induced upstream hydrological changes and sea level rise, which are expected to exacerbate flood risks and salinity intrusion. Because of these drivers, the Mekong Delta is ranked as one of the world's most vulnerable river deltas (Adger, 1999; Nicholls et al. 2007). Regional assessments (e.g. Wassmann et al. 2004; MoNRE, 2009; MRC, 2011a; SIWRP, 2012; Tri et al. 2012) also suggest more frequent and severe floods caused by upstream hydrological changes and rising sea levels. In response, decision makers and planners in the delta have developed several adaptation plans to cope with the anticipated impacts. These include the Climate Change Adaptation Plan for Mekong Delta (JICA, 2010), the Mekong Delta Plan (MDP, 2013), the Mekong Delta Masterplan for water resources management under climate change and sea level rise (SIWRP, 2012). Concerning floods, existing plans often emphasize the importance of, and focus on addressing extreme events where potential impacts and vulnerabilities are most critical. These plans, however, also stress the lack of reliable data and information on future flood hazard and flood risk, especially those concerning extreme, low probability events.

A number of previous flood studies are available for the Mekong basin and delta (e.g. Västilä et al. 2010; Dung et al. 2011, 2015; Tri et al. 2012, 2013; and Piman et al. 2013). Dung et al. (2011) developed and calibrated a one-dimensional hydraulic model using existing river network, control structures and hydrological measurement data. Västilä et al. (2010), Tri et al. (2012) and Piman et al. (2013) used hydrological and hydraulic models to investigate the Mekong's future flood regime, focusing on changes in flood's magnitude and timing under climate change and other upstream socio-economic development scenarios. Delgado et al. (2012) and Dung et al. (2015) employed statistical analyses on observed data to study historic flood regimes and associated uncertainties. Reflecting on difficulties related to limited long-term observation data, Delgado et al. (2012) suggested to use long-term model simulations to study extreme floods in the Mekong basin. Most previous studies on future floods in the Mekong Delta ignore both sea level rise and local land subsidence. While both these factors are likely to increase future flood hazard, especially in combination with increases in precipitation extremes. The current land subsidence rate in the delta is 1 to 4 cm yr^{-1} (Erban et al. 2014). Land subsidence in combination with sea level rise due to global warming is likely to have large impacts on the coastal zone of the delta. Data and information concerning future extreme floods combining different aspects of future global change are still largely missing, although this information is utterly needed for flood management and strategic delta planning.

This research addresses the knowledge gaps discussed above on extreme flood hazard under climate change. We first set up, calibrate and validate a model chain to simulate floods under upstream hydrological changes and sea level rise (Sections 4.3.1; 4.3.4 and 4.4.1). We also prepared input data of various types for our scenario assessments (Sections 4.3.2 and 4.3.3). Next, our simulation results are presented, showing substantial increases in flood magnitude and frequency under sole upstream hydrological changes, sole sea level rise and these two drivers combined (Section 4.4.2; 4.4.3 and 4.4.4, respectively). We then discuss the results and reveal important implications of increasing future flood hazard for flood management and climate change adaptation (Section 4.5). Section 4.6 summarizes the main findings and finalizes with some reflections on understanding and managing flood dynamics in complex deltaic systems.

4.2. Study area

The Mekong Delta starts in Kratie in Cambodia (see location in Figure 4.1) and the river flows through the Cambodian floodplain before entering Vietnam through two main river branches, namely the Mekong and the Bassac. A substantially larger portion (over 70%) of the delta's total area is located in Vietnam, and this paper therefore only focuses on the Vietnamese part of the delta. After entering Vietnam, the river branches flow in the South-Eastern direction, almost parallel to each other (Figure 4.1). These two main branches gradually divide into smaller tributaries along their courses and drains into the East Sea after about 200 km from the Vietnam-Cambodia border.

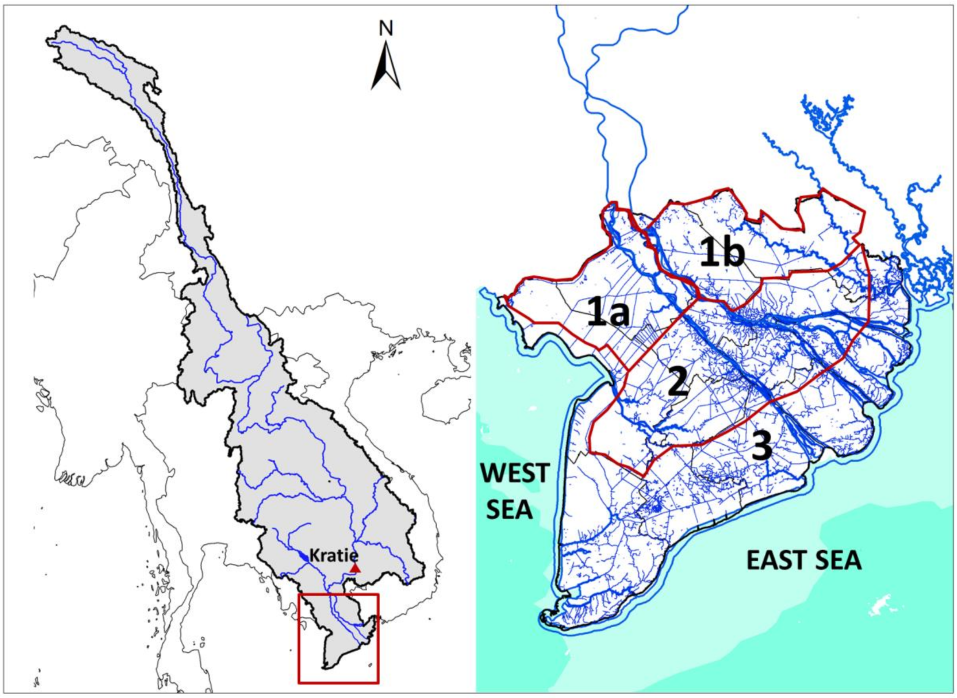

Figure 4.1 The Mekong River basin (left) and river network of the Vietnamese Mekong Delta (right). The whole delta is divided into different regions: the upper delta including the Long Xuyen Quadrangle (Zone 1a) and the Plain of Reeds (Zone 1b); the middle delta (Zone 2); and the coastal delta (Zone 3).

The Mekong Delta can be divided into three zones based on their distinctive soil-water characteristics (MDP, 2013). The upper delta is characterized by a fresh water environment and features the delta's main floodplain in the Long Xuyen Quadrangle, Plain of Reeds and the area between the Mekong and the Bassac branches (see Figure 4.1). The middle delta features fertile soil and favourable water conditions for agriculture (mainly rice production), horticulture and aquaculture. Some of the delta's major urban areas are also located in the middle delta, including Can Tho - 1.4 million inhabitants, My Tho - 225,000 inhabitants and Vinh Long - 150,000 inhabitants (GSO, 2014). This region's hydrological regime exhibits interactions between upstream river flow and tidal regime from the sea. Floods in this area come in moderate magnitudes and generally cause no substantial damages (JICA, 2010). The coastal delta stretches along the coastline, including the Ca Mau peninsula. The hydrological regime in the coastal delta is strongly driven by the tidal regime due to direct exposure to the West and East Seas. The region's aquatic environment is dominantly characterized by brackish and saline water.

The flood season in the Mekong Delta starts in July and lasts until December. Floods are mostly driven by the Mekong's streamflow and the tidal regime (Wassmann et al. 2004). The Mekong's high river flows are often caused by monsoon-driven rainfall in catchment areas in Thailand, Laos PDR, Cambodia and the Vietnamese Central Highland (MRC, 2005). Tropical cyclones during the wet season can also generate wide-spread rainfall in the upstream areas (Darby et al. 2013), causing rapid rising of the Mekong's runoff and river flow. Tidal activities in the West and East Seas also influence flood dynamics. High tides cause local inundation along the coastal zone and enhance floods in the delta's floodplains when coinciding with high upstream inflow. The major flooded areas locate in the floodplains in the upper delta, whereas localized inundations occur in the middle delta and along the coast. Extreme floods in the Mekong Delta pose an important threat to safety and economic activities (MRC, 2005). Recent examples of the severe floods include the events in 2000 and 2011, with estimated economic losses of over $200 million (Cosslett and Cosslett, 2014) and $50 million (MRC, 2011b), respectively. Furthermore, earlier studies suggest potentially increasing flood hazard caused by upstream changes and sea level rise, emphasizing the delta's critical vulnerability to these external stressors (Wassmann et al. 2004; Piman et al. 2013; Erban et al. 2014).

4.3. Methodology

4.3.1. The model chain

Floods in the Mekong Delta are driven by multiple drivers, most importantly upstream inflows, downstream sea level and the within-delta hydrological network (i.e. rivers, canals and control structures). We developed a model chain (see scheme in Figure 4.2) to integrate all these drivers in the simulations, allowing to quantify the impacts of changes in upstream inflows and downstream water levels on flood characteristics, both combined and separately.

The model chain consists of three main modelling tools, namely a weather generator (Buishand and Brandsma, 2001; Leander et al. 2005), a basin-wide hydrological model, i.e. the VMod (Lauri et al. 2006), and a Mekong Delta hydraulic model (Dung et al. 2011). The weather generator was used to extend the relatively short-term (30-yr) climate data time series to long-term (1000-yr) synthetic climate data series (Steps 1 and 2 in Figure 4.2). This synthetic climate data was then used as an input data to the VMod hydrological model to simulate the Mekong basin's hydrology and produce discharge time series at Kratie – the Mekong Delta inlet (Steps 3 and 4). The river discharge time series at Kratie were used as upstream boundary condition in the hydraulic model to simulate discharges and water levels in the delta (Steps 5 and 6). The hydraulic model also required data on river network and downstream water level to simulate the delta's hydrology. Details of each modelling tool are described in the following sections.

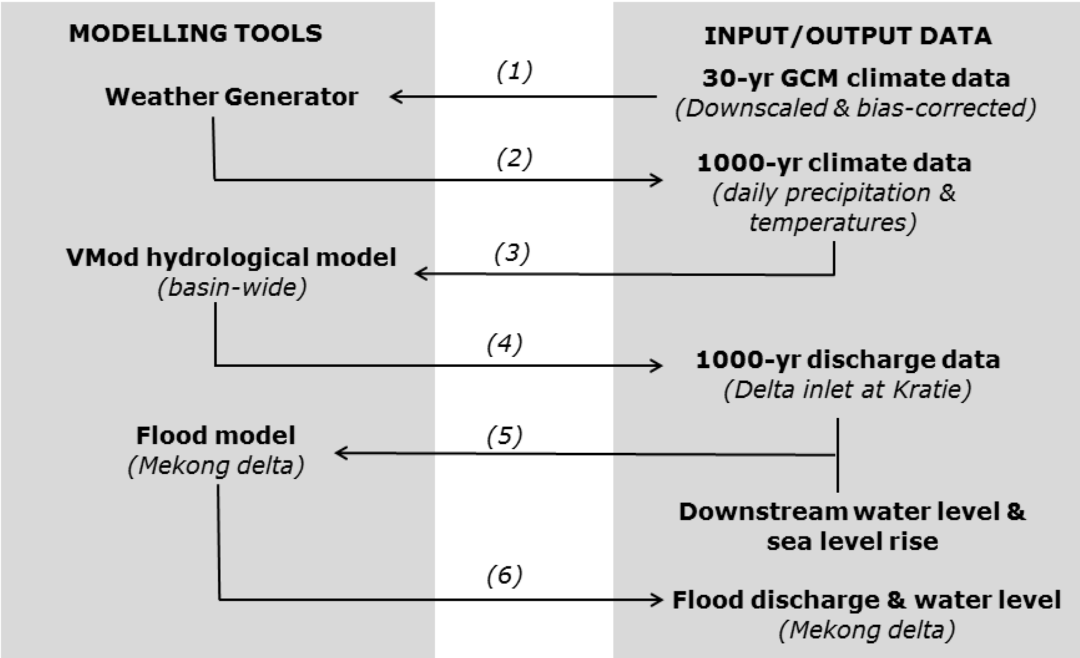

Figure 4.2 The model chain for basin-wide hydrology and in-delta flood simulations

The weather generator

The weather generator was used to produce long-term, synthetic climate data (i.e. daily temperatures and precipitation) from short-term, original GCM-based data. The synthetic data is statistically similar ($p<0.05$), although not identical to the original data. However, since this synthetic data covers a much longer timespan (i.e. 1000-yr), they allow for more robust statistical inferences compared to those applied on the original 30-yr data (Wilks & Wilby, 1999). In particular, by producing long-term climate data, we could produce long-term data of river discharges and water levels in the next steps of the model chain. These long-term hydrological time series are suitable for probabilistic estimation of extreme floods (Leander et al. 2005; te Linder et al. 2011).

We used a multi-site, stochastic weather generator (Buishand and Brandsma, 2001; Leander et al. 2005) to produce synthetic climate data. The weather generator uses the nearest neighbours resampling technique to simultaneously simulate daily temperature and precipitation data at multiple locations. First, each day of the original climate data is represented by a feature vector, which contains statistical properties of the weather condition for that day. These properties include averages of daily temperature and precipitation, and the fraction of wet locations i.e. daily precipitation amount above zero. Synthetic data for each day is resampled from its previous day's nearest neighbours. These nearest neighbours are the days in the original data that have smallest weighted Euclidean distance to the feature vector of the current day (Buishand and Brandsma, 2001). The weather generator effectively reproduces the autocorrelations of daily climate data (Leander et al. 2005), being very important for river basins with consecutive rainy days like the Mekong. Additionally, this multi-site weather generator allows to represent spatial correlations of rainfall events across multiple locations. This feature is highly relevant to the Mekong case, especially during monsoon season when rainfall events often occur simultaneously at multiple sites, leading to rapid increases in runoff and river discharge. Detailed description and underlying theories for the weather generator can be found in Buishand and Brandsma (2001).

The Mekong basin hydrological model

We used a modelling setup by Hoang et al. (2016) and Lauri et al. (2012) to simulate the hydrology of the whole Mekong basin. This setup is based on the VMod hydrological model (Lauri et al. 2006), allowing to simulate daily river discharges at multiple locations with a spatial resolution of 5x5 km. The model setup consists of several raster datasets, including spatial data on flow direction, land use characteristics, and soil properties as described in Hoang et al. (2016). Land-surface and runoff processes are simulated on a daily time step, using four climate input variables, namely maximum, minimum, average air temperatures, and precipitation. A detailed description of the VMod model's algorithms and equations is available in the model manual (Lauri et al. 2006). The model setup for the Mekong was thoroughly calibrated and validated by Hoang et al. (2016). The hydrological model provides daily discharge time series at Kratie, which will be used as input data for the Mekong Delta flood model.

The Mekong Delta flood model

The Mekong Delta flood model (hereafter, the flood model) was developed by Dung et al. (2011) based on the MIKE-11 modelling suite. This hydraulic model was developed to simulate flood discharges and water levels in the Mekong Delta, using 1-dimensional representations of the flood plain and river network. The modelling domain covers an area of 55,000 km^2, stretching from upstream inlet (at Kratie, Cambodia) down to the river mouths along the Vietnamese coast. The whole delta is represented by 4,235 branches equivalent to 26,376 computational nodes. Discharges and water levels at each node is computed using daily discharges at Kratie and hourly sea water levels at the ending nodes (at the coast) as upstream and downstream boundary conditions, respectively.

More information on modelling setup and calibration techniques is provided in Dung et al. (2011). In this study, we used the flood model to produce long-term (1000-yr) synthetic data series of water levels at each computational node and subsequently conducted spatially explicit flood probabilistic estimation.

4.3.2. Climate change scenarios

We downscaled and bias-corrected climate data from five Global Circulation Models (GCMs) under the Coupled Models Intercomparison Project 5th phase (CMIP5). The GCMs were selected based on evaluations of their ability to reproduce historic climatic conditions. In particular, we consulted evaluations from Silmann et al. (2013), Huang et al. (2014), and Hasson et al. (2016) and selected the five models for our climate change scenarios preparation. For each GCM, we prepared climate change scenarios for two Representative Concentration Pathways (RCPs), namely the RCP4.5 (Thomson et al. 2011) and RCP8.5 (Riahi et al. 2011). Given the focus on high-end climate change, we excluded the lowest greenhouse gases concentration scenario (i.e. the RCP2.6). Furthermore, for each GCM we selected one RCP that projects larger increase in high river flow. Based on the high flow analysis in Hoang et al. (2016), the following scenarios were included: ACCESS1-0-RCP8.5 (ACCESS); CCSM4-RCP8.5 (CCSM); CSIRO-Mk3.6.0-RCP8.5 (CSIRO); HadGEM2-ES-RCP4.5 (HadGEM); MPI-ESM-LR-RCP8.5 (MPI). For each GCM, daily climate data required by the VMod hydrological model were extracted, including precipitation, average, maximum and minimum temperatures. Climate data was prepared for baseline (1971-2000) and future (2036-2065) periods.

Original GCM data was first downscaled to a 0.5°x0.5° grid using bilinear interpolation. Climate data was then subjected to a statistical bias-correction, using the method of Piani et al. (2010). This monthly, parametric bias-correction uses transfer functions to match statistics of historic GCM data to those of the observed climatic conditions. The transfer functions are then applied on future GCM data in order to correct biases in the future climate scenarios. In this study, we used the APHRODITE (Yatagai et al. 2012) dataset for bias-correction of precipitation while the WATCH forcing dataset (Weedon et al. 2011) was used for bias-correction of temperatures. Both datasets were developed based on observed data and were proved of adequate quality to represent historic climatic and hydrologic conditions of the Mekong basin (Lauri et al. 2014; Hoang et al. 2016). Finally, bias-corrected climate data was extended to long-term (1000-yr) synthetic data using the weather generator, allowing for further simulations and analyses of extreme floods.

4.3.3. Sea level rise scenario

We developed a relative sea level rise scenario based on a regional projection by the U.S. Geological Survey (Doyle et al. 2010). This projection is developed specifically for the Mekong Delta to support regional impact assessment. Sea level data up to 2100 is constructed using historic data, future climate change induced sea level rise and land subsidence rates. Historic sea level data is prepared from gauged data and global sea level rise rates are extracted from the global projection under the IPPC's fourth assessment report

(Meehl et al. 2007). We selected the A1FI-based sea level scenario from Doyle et al. (2010) to develop a high-end scenario. This scenario is largely consistent with the RCP8.5, where both represent the highest greenhouse gases emission storylines (Riahi et al. 2011). Similarly, a 9 mm yr^{-1} subsidence rate is selected, which is closest to the observation-based rate by Erban et al. (2014). Based on Doyle et al.'s (2010) projection, we calculated the absolute increase in yearly mean sea level between the 2000-2010 and 2050-2060 periods. Since Doyle et al.'s (2010) data only covers the 2000-2100 period, our sea level rise scenario's timing is slightly different from that of climate change scenarios (i.e. 1971- 2000 versus 2036-2065). This difference, however, will not affect the derived impact signals and only marginally influence impacts' magnitude. Our analysis resulted in a relative sea level rise of +0.60 m, which will be included in our flood simulations.

4.3.4. Model calibrations and validations

All models in the modelling chain were carefully calibrated and validated to ensure reliable simulation results. Since calibration and validation of the VMod hydrological model and the Mekong Delta flood model are discussed in details by Hoang et al. (2016) and Dung et al. (2011), this section focuses mostly on the weather generator.

The VMod hydrological model is calibrated and validated for the Mekong basin by Hoang et al. (2016). The model shows good performance in reproducing both the annual hydrological cycle and discharge extremes. The Nash-Sutcliffe efficiency indices (Nash and Sutcliffe, 1970) calculated from daily discharge during the 1981-2001 period for seven main gauging stations range from 0.88 (at Vientiane – Laos PDR) to 0.96 (at Nakhon Phanom – Thailand), showing reliable simulation of the Mekong's hydrology. High river flows were also realistically reproduced by the model, with a relative bias of less than 15% in the Q5 index (discharge value exceeded 5% of the time) at the delta inlet at Kratie.

The Mekong Delta flood model is calibrated and validated through a multi-objective auto-calibration procedure, showing relatively good simulation results for both water levels and inundation extent (Dung et al. 2011). The model is calibrated for two main objectives, namely optimal flood water level and optimal representation of the inundation extent. Simulation of flood water level is optimized using measured data at multiple gauging stations whereas inundation extent is optimized using remotely-sensed satellite images from the ENVISAT Advanced Synthetic Aperture Radar (Dung et al. 2011).

The weather generator is calibrated for the Rhine (Buishand and Brandsma, 2001) and Meuse River basins (Leander et al. 2005), showing a good representation of the observed conditions. We further calibrated and validated the weather generator for the Mekong basin. For calibration, we adjusted two parameters of the nearest-neighbour resampling algorithm, namely the width of the sampling window and number of nearest neighbours for resampling climate data. After each parameter adjustment, we compared original and synthetic precipitation and temperature statistics (i.e. daily averages and probability distributions) to select the optimal parameter configurations. In particular, we used the two-sample Kolmogorov-Smirnov (K-S) test to check whether the original and the synthetic data have the same probability distribution – implying reliable performance of the weather generator. This test was done on a grid-by-grid basis to compare daily mean precipitation and daily mean temperature time series. Since precipitation extremes are highly relevant for the Mekong's hydrology, we also applied Kolmogorov-Smirnov (K-S) test on monthly maximum five-day precipitation amount (Zhang et al. 2011). Furthermore, we compared river discharges simulated from original and synthetic climate data as an indirect validation of the weather generator and to address the implications of uncertainties in the synthetic climate series on simulated hydrology.

4.3.5. Flood probabilistic estimation and mapping

The main aim of this study is to estimate flood water level and flood extent under specific probabilities (i.e. return values). Such estimation was done by fitting long-span data of yearly maximum water levels from the flood model to a suitable probability distribution. We selected the Generalized Extreme Value distribution (GEV) to estimate yearly maximum water levels at the model's nodes. The GEV is considered a suitable probability distribution for analysing climatic and hydrological extremes, including water level's maxima (Stedinger et al. 1993; Dung et al. 2015). This distribution is also proved highly suitable for probabilistic estimation of flood discharges and volumes for the Mekong basin compared to other distributions (Dung et al. 2015). We fitted the 1000-yr data to the GEV distribution and subsequently estimated maximum flood water level under multiple return periods of 20-yr (moderate flood), 100-yr (extreme flood) and 500-yr (very extreme flood).

Maps to present flood depth and flood extent under multiple return periods and scenarios (i.e. upstream hydrological changes and sea level rise) were developed using a two-steps procedure. First, yearly maximum water levels at the model's nodes were interpolated to a 1x1 km raster using inverse distance weighting interpolation. Flood depth under different return values were then calculated by subtracting the flood water level raster by the elevation data prepared from the 90 m SRTM dataset (Jarvis et al. 2008).

4.4. Results

4.4.1. Calibration and validation results

Here we focus on the weather generator's performance. For details about calibration and validation of the VMod hydrological model and the flood model see Hoang et al. (2016) and Dung et al. (2011), respectively.

The weather generator's performance was checked using direct and indirect validations. Direct validation of temperature and precipitation shows good agreement between original and synthetic data. The two-sample Kolmogorov-Smirnov test shows no significant difference ($p<0.05$) between original and synthetic data for at least 97% of the total 283 grid cells for 30-yr mean daily precipitation and temperature, respectively (Table 4.1). The weather generator's performance for precipitation extremes (i.e. the monthly maximum five-day precipitation amount Rx5) reduces slightly, showing no significant difference ($p<0.05$) between 88% and 98% of the total grid cells, depending on the climate dataset in question.

Table 4.1 Weather generator's direct validation of simulated temperature and precipitation using two-sample Kolmogorov-Smirnov test. Numbers show percentages of grid cells having a similar probability distribution.

Climate data	Daily mean precipitation	Daily mean temperature	Precipitation extreme Rx5
Baseline	100%	100%	99%
ACCESS	99%	100%	99%
CCSM	100%	100%	98%
CSIRO	100%	98%	96%
HadGEM	97%	100%	88%
MPI	100%	100%	98%

Additionally, we compared river discharge simulated from original and synthetic climate data during 1971-2000 as indirect validation of the weather generator. Figure 4.3 shows the flow duration curves for original, synthetic and observed river discharges at Kratie under all climate datasets. Overall, both original and synthetic discharge show good agreement with observed data, indicating that the combination of weather generator and the VMod model reproduce the Mekong's discharges with sufficient accuracy. The Nash-Sutcliffe efficiency indices under individual climate datasets range from 0.54 (fair) to 0.75 (very good), proving the model chain's capability to reproduce river discharges as simulated by the original climate forcing data. Based on these validations, we conclude that the weather generator is suitable to produce long-term synthetic climate data for flood simulation.

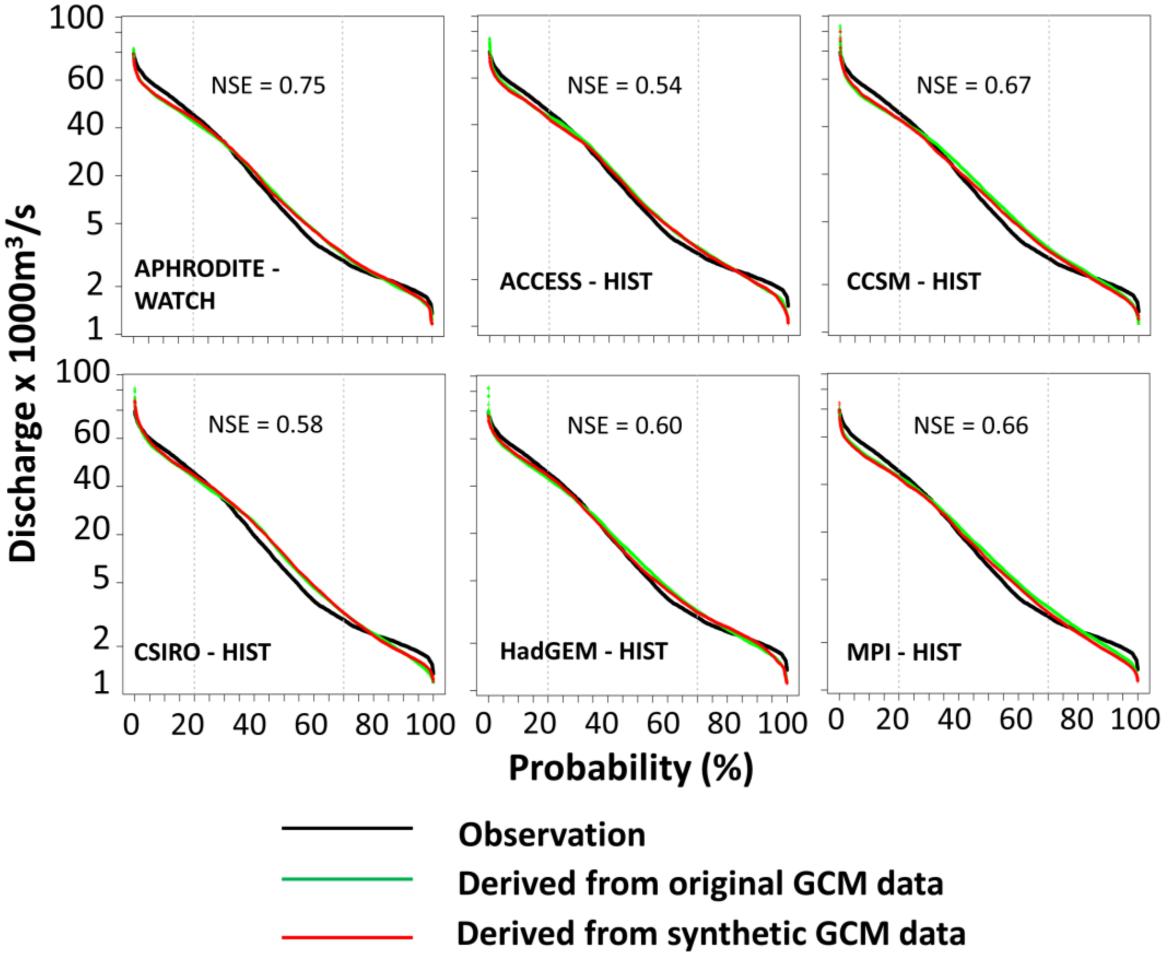

Figure 4.3 Flow duration curves at Kratie from observed (black), original (green) and synthetic (red) GCM baseline climate data. Note: y-axis has log10 scale

4.4.2. Climate change impacts

Climate change scenarios consistently show increases in temperature in the Mekong basin. Basin-average temperature is projected to increase between +1.8°C (HadGEM model) and +3.4°C (ACCESS model) for the future period (2036-2065) compared to the baseline period (1971-2000). Basin-average annual precipitation increases between +4% (CSIRO model) and +7% (CCSM model). Although precipitation increases at the basin level, certain regions also show slight reductions of less than 5% annually. Details about projected temperature and precipitation changes are available in Hoang et al. (2016).

These changes in temperature and precipitation result in higher discharge of the Mekong's river for the future period. Hydrological simulations by the VMod model show an increase between +2% (CSIRO-RCP8.5) and +10% (CCSM-RCP8.5) in annual river discharge at Kratie. The scenarios ensemble mean projects +7% higher annual discharge at Kratie. Flood season river discharge also increases substantially under all climate change scenarios. Figure 4.4 presents the estimated return values of peak river discharge corresponding to different frequencies for the baseline and future periods. Figure 4.4 also illustrates that peak discharges tend to occur at much higher frequencies under future climate change and the signal is consistent across all five scenarios. For example, peak discharge under a 100-yr flood is projected to reach 84x10^3 m^{3}s^{-1} (ranging from 74x10^3 m^{3}s^{-1} to 88x10^3 m^{3}s^{-1}) compared to 70x10^3 m^{3}s^{-1} under the baseline period.

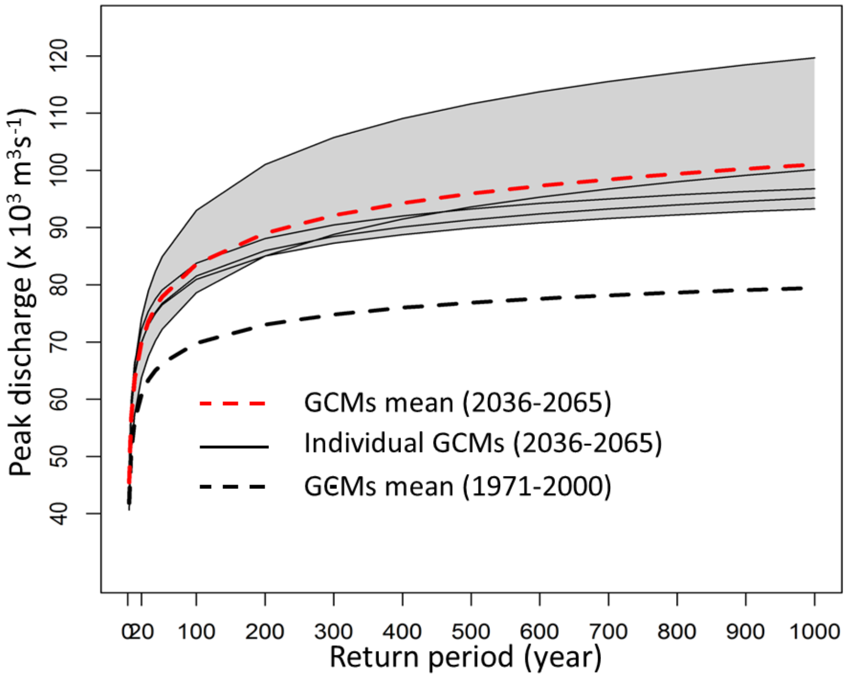

Figure 4.4 Estimated return values of peak river discharge at the Mekong Delta inlet (Kratie, Cambodia) under future climate change

As a result of increasing upstream inflow, flood hazard increases substantially in the Mekong Delta. Figure 4.6-A shows that flood depth in the floodplain increases between +0.2 m to +0.8 m under upstream changes. Additionally, flood depth increases more under extreme, low-probability events. For example, Figure 4.6-A also shows that flood depth typically increases between +0.4 m and +0.8 m under 500-yr floods while 20-yr foods only show about +0.2 m to +0.4 m increases.

Regarding flood extent, Figure 4.5-C and Figure 4.6-A show that the flood zone tends to expand towards the southern and eastern parts of the delta under upstream changes. These expansions follow the flow directions of the main river branches (i.e., the Mekong and the Bassac), through which flood water is routed from upstream towards the sea. Although the flood zone expands and flood depth increases under upstream changes, the flood's spatial distribution remains essentially similar to that of the baseline situation. In particular, the most severely flooded areas under upstream changes only remain in the upper delta, including the Long Xuyen Quadrangle, the Plain of Reeds and the riverine areas between the Mekong and the Bassac (Figure 4.5-C). Additionally, the Plain of Reeds shows larger impacts, i.e. larger flood zone and higher flood depths than the Long Xuyen Quadrangle. This difference is explained by higher protection capacity (mainly through dikes) which has been continuously upgraded in the Long Xuyen Quadrangle compared to a relatively natural floodplain in the Plain of Reeds (SIWRP, 2012). Lastly, upstream changes impacts remain mostly within the upper delta and gradually reduce when moving towards the middle and coastal delta. Figure 4.6-A shows that rises in flood depths are mostly visible in the upper delta while they diminish quickly after Vam Nao (see location mark in Figure 4.7). Downstream areas along the coast, including Ca Mau, Tra Vinh, Soc Trang and Ben Tre are not projected to experience strong increase in flood hazard under sole upstream changes.

4.4.3. Sea level rise impacts

Flood depth and its changes under +0.6 m sea level rise compared to baseline situation are presented in Figures 4.5-B and 4.6-B, respectively. Compared to the upstream hydrological changes, sea level rise impacts are larger at the coastal delta and gradually reduce when moving upstream. Furthermore, sea level rise introduces floods to the currently relatively safe areas in the coastal and middle delta. Figure 4.5-B shows that sea level rise results in vast flood zone in the coastal and middle delta, especially at the coastal provinces. Flood depth at the coastal delta ranges between 0.5 m to 2.0 m, exhibiting an increase between +0.4 m and +0.7 m compared to baseline situation (figure 4.6-B). The Ca Mau Peninsula in the coastal delta is the most affected region under sea level rise, with an increase of above +0.5 m in flood depth. While sea level rise impacts are visible in the coastal and middle delta, the upper delta shows little to almost no increase in flood depth.

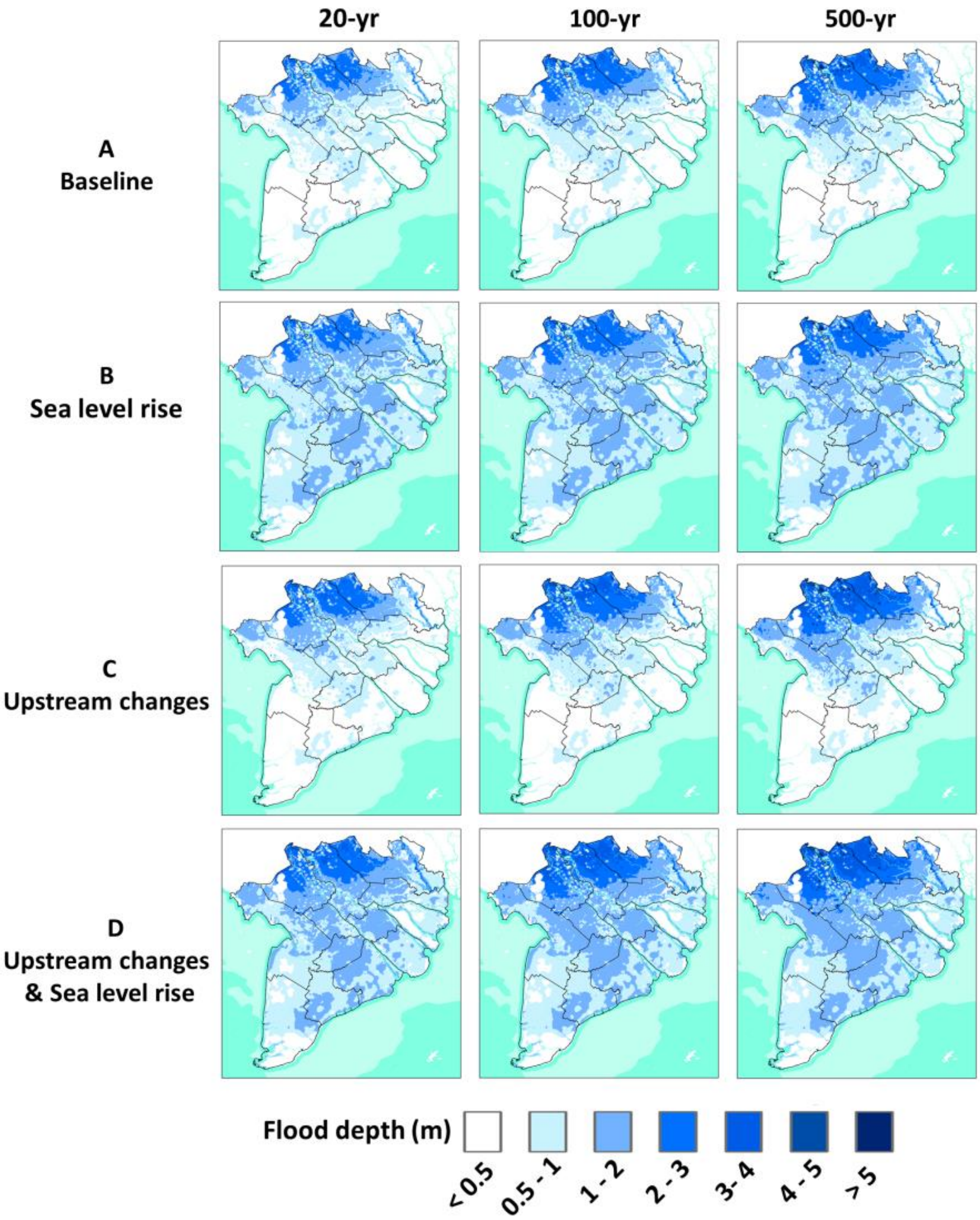

Figure 4.5 Maximum flood depth for baseline (row A); sole sea level rise impacts (row B); sole upstream hydrological changes impacts (row C) and two drivers combined (row D). Results are presented for 20-yr (moderate floods, left column); 100-yr (extreme floods, middle column) and 500-yr (very extreme floods, right column) return periods.

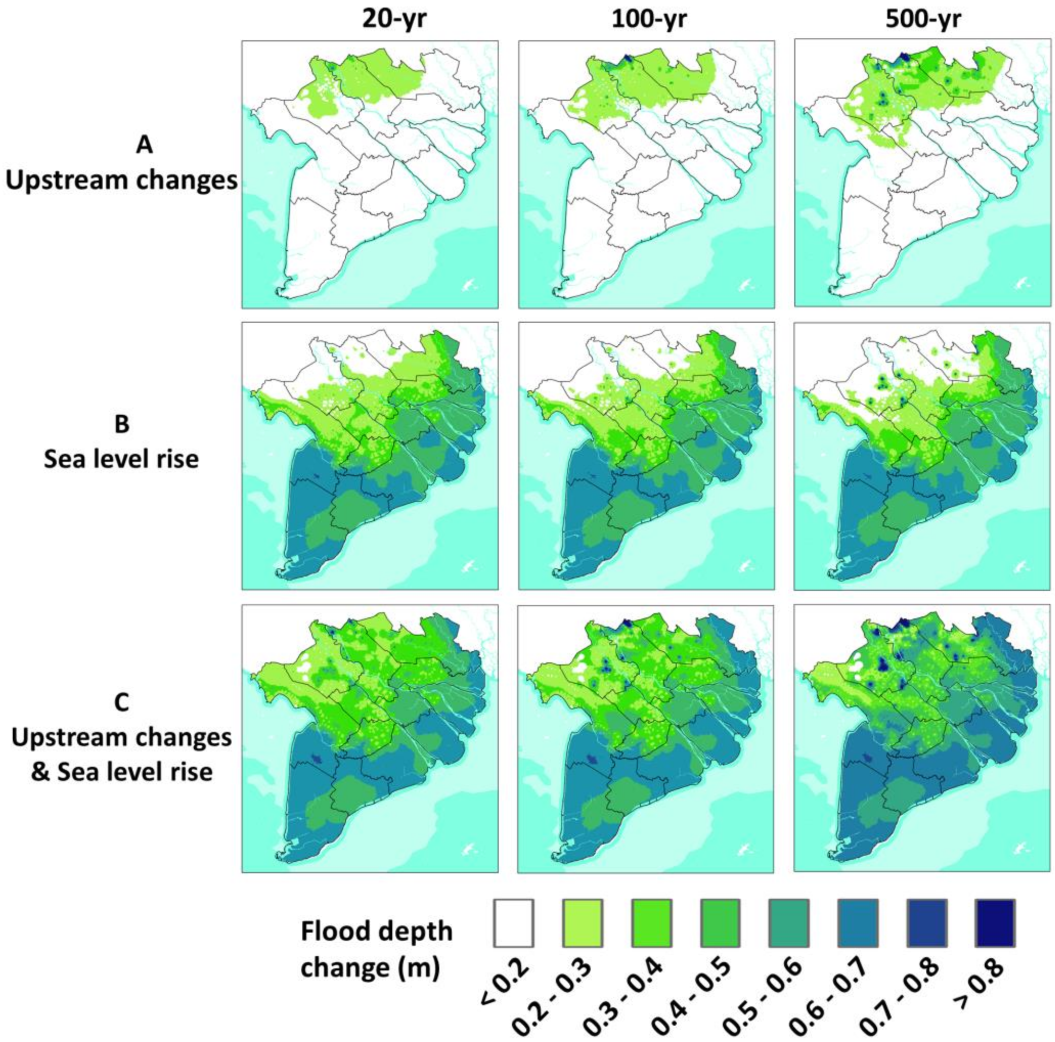

Figure 4.6 Flood depth increases caused by sole upstream hydrological changes (row A); only sea level rise (row B) and two drivers combined (row C). Results are presented for 20-yr (moderate floods, left column); 100-yr (extreme floods, middle column) and 500-yr (very extreme floods, right column) return periods.

Simulation results also show that a +0.6 m sea level rise creates more substantial impacts on floods compared to upstream increases in inflow under climate change. First, sea level rise impacts cover a markedly larger area than that under upstream changes. Figure 4.6-A and 4.6-B show that upstream changes only affect the upper delta whereas the larger areas in the middle and coastal delta are affected by sea level rise. Second, changes in flood depth at different locations show that sea level rise impacts are often higher than that of upstream change, except for three locations in the upper delta, i.e. Tan Chau, Chau Doc and Vam Nao (see locations in Figure 4.7).

4.4.4. Combined impacts of sea level rise and upstream hydrological changes

Overall, upstream inflow increases under climate change combined with sea level rise exacerbate flood hazard throughout the whole Mekong Delta. Contrasting to the more prevailing impacts of upstream hydrological change in the upper delta and the more prevailing sea level rise impacts in the coastal delta, flood depth increases in all three delta regions under these two drivers combined (see Figure 4.6-C). Figure 4.5-D shows that flood depth remains highest at the upper delta and gradually reduces further downstream. Under very extreme floods (i.e. 500-yr return period), flood depth ranges between 3 m to 5 m at the Long Xuyen Quadrangle and the Plain of Reeds. The middle and coastal delta exhibit flood depth ranging from 0.5 m to 3 m under floods of the same probability. Despite the higher flood depth in the upper delta, increases in flood depth are, however, higher at the coastal delta due to more substantial impacts of sea level rise. Figure 4.6-C shows that flood depth increases by 0.5 m to 0.7 m at the coastal zone under 100-yr flood while increases in the upper delta typically range between +0.3 to +0.4 m. Extreme, low probability floods under both upstream changes and sea level rise, however, show an exception where flood depth actually increases more substantially at some localized flood zones in the upper delta. For instance, flood depth under 500-yr floods increases up to +0.9 m at some deeply flooded hotspots in the upper delta (see Figure 4.6-C).

Upstream hydrological changes and sea level rise tend to intensify each other's impacts on flood, resulting in stronger combined impacts than linearly summed impacts of each individual driver. Figure 4.7 shows that increasing flood depth under the two drivers combined are markedly higher than the summed increases under each driver. The intensified impacts under two drivers are especially relevant at locations in the upper delta, including Tan Chau, Chau Doc, Vam Nao and Long Xuyen. Impacts intensification effect is primarily explained by reduced water transfer capacity, which is caused by lower hydraulic gradient between the upper and coastal delta regions under climate change.

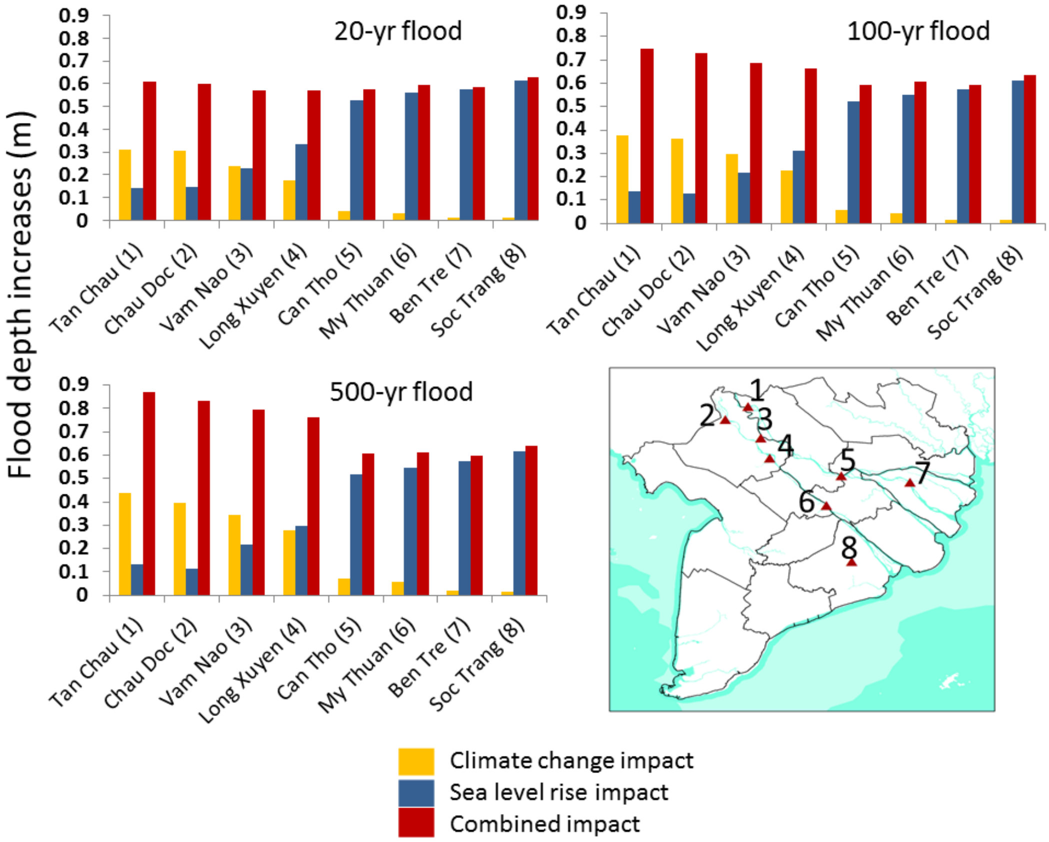

Figure 4.7 Flood depth increases at representative locations in the Mekong Delta under separate and combined impacts of upstream hydrological changes and sea level rise.

4.5. Discussion

We quantified changes in magnitude and frequency of future floods in the Mekong River Delta under climate change induced upstream hydrological changes and sea level rise. For this purpose, we developed a modelling chain to simulate future floods, incorporating both upstream changes and downstream sea level rise. Our long-term climatic and hydrological data allows for statistically robust probabilistic estimates of future flood hazard. As such, this study provides new useful insights on how flood hazard will increase under climate change. Furthermore, our results reveal important implications for flood management and strategic delta management.

Our results show substantial increases in flood hazard under high-end upstream climate change and sea level rise scenarios. This impact signal is in line with those projected by earlier studies using physical modelling approaches including Wassmann et al. (2004), Västilä et al. (2010), Tri et al. (2012, 2013) and Piman et al. (2013), and statistical approaches (e.g. Dung et al. 2015). First, upstream climate change results in more frequent and higher river's peak discharge draining into the delta (Section 4.4.2). Consequently, these changes in the upstream boundary condition increase the frequency and magnitude of flood events in the downstream delta. Second, changes in the downstream boundary condition caused by rising sea level also contribute largely to increased flood hazard (Section 4.4.3). Due to differences in the nature and magnitude of upstream changes and sea level rise, their impacts on floods show distinctive features (Section 4.4.4). In particular, upstream climate change impacts are more prevalent in the upper delta, whereas sea level rise mostly affects the coastal and middle delta zones.

4.5.1. Consequences and management implications

The projected increasing flood hazard under climate change induced upstream hydrological changes and sea level rise reveal important implications for flood management and research in one of the largest and most densely populated deltas in Southeast Asia. First, an increase of up to +0.8 m in flood depth in the upper delta are expected to result in hazards that exceed the protective capacity of the current dike system in this part of the delta (SIWRP, 2012). Secondly, sea level rise and (to a lesser extent) upstream hydrological changes, will expand the flood zone towards the middle delta and coastal provinces in the coastal delta. New flood hazard in these currently relatively safe areas requires special attention to improve financial, technical and institutional capacities to prepare for these new challenges. Of special importance in this regard is the need for further research to identify hotspots where flood vulnerability is most critical. Lastly, substantial increases in flood hazard throughout the Mekong require strategic choices in flood management and delta management. Adapting to the increased flood hazard could be pursued by upgrading the flood protection system (e.g. dikes and flood water retention zones) or improving flood resilience, (e.g. living with flood) or through a combination of both approaches (Käkönen, 2008; Marchand et al. 2014). Our results can be used as physical boundary conditions for making such decisions, and for testing effectiveness of flood management options proposed by planners and decision makers in the delta.

4.5.2. Limitations and way forward

We acknowledge three major limitations in this research. The first limitation relates to the use of sea level rise scenario. Given our primary interest to investigate the upper bound of sea level rise impacts and the heavy computational demands of the flood model, we considered only one sea level rise scenario rather than having a range of possible scenarios in our analysis. The second limitation relates to upstream hydrological change, where only GCM-based climate change scenarios were analysed. Including highly spatially resolved climate projections from the regional climate downscaling experiment CORDEX (Giorgi and Gutowski, 2015) could potentially improve our assessment's accuracy, but this data is not yet available for the Mekong region. In addition to climate change, the

Mekong's hydrology and flood regime are also driven by other anthropogenic drivers, such as land use change and hydropower dam construction (Hoanh et al. 2010; Lauri et al. 2012; Arias et al. 2013). Additionally, configurations of the current river network and flood protection dikes within the delta will likely alter the flood dynamics (Le et al. 2007; Hannu et al. 2012; Ziv et al. 2012). Including these drivers, however, is beyond the scope of this study. We therefore suggest taking these drivers into account in future studies.

4.6. Conclusions

We quantified impacts of climate change on future flood hazard in the Mekong Delta, focusing on extreme events. Although climate change is expected to induce upstream hydrological changes and downstream sea level rise, little is known about how these changes impact flood hazard in the delta. We aimed to fill this important knowledge gap by using a model chain to assess future flood hazard under multiple scenarios of climate change induced upstream changes and sea level rise. The study yields several important findings, which contribute to further understanding about the future flood dynamics and also reveals implications for flood management.

We found that higher upstream inflow and sea level rise induced by climate change will substantially increase the magnitude and frequency of future floods throughout the whole delta. Their separate impacts, however, will be distributed differently across different zones. Upstream hydrological changes mainly affect the current floodplain in the upper delta, whereas sea level rise introduces floods to the currently safe areas in the coastal zone. Additionally, upstream hydrological changes and sea level rise together amplify their impacts, resulting in the most severe flood hazard. This impact intensification shows that flood dynamics is complex and dependent upon multiple drivers. We therefore suggest to better integrate multiple drivers in assessing flood hazard in deltaic regions such as the Mekong Delta. Lastly, increased flood hazard under climate change poses critical safety challenges and thus calls for better flood protection and more flood resilient developments. Our probabilistic estimates of future extreme flood hazard for the Mekong Delta provide benchmarks for developing proper flood management strategies and strategic delta management plans in a broader sense.

Acknowledgement

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CHAPTER 5

Managing flood risks in the Mekong Delta: How to address emerging challenges under climate change and socioeconomic developments?

Abstract

Climate change and accelerating socioeconomic developments create critical challenges for flood risk management in the Vietnamese Mekong Delta. Without timely responses, these challenges can hamper management efforts, thus posing serious threats for flood safety and sustainable developments. This is one of the first studies to (i) systematically identify key challenges for managing flood risk, and (ii) develop tailored intervention measures and strategies. We used a novel approach to analyse data collected from systematic literature review and expert surveys. Statistical inferences were combined with qualitative techniques (i.e. content analyses) to gain insights about the challenges and furthermore, how to effectively address them. We identified 19 challenges from literature, of which 12 were considered important by the experts. The Top-3 challenges include weak collaboration, conflicting interests, and low responsiveness to new issues. Although the challenges are diverse and multifaceted, critical challenges predominantly arise from the current governance and institutional settings. The identified mismatch between this predominant type of challenge and the currently implemented technical measures requires adapting the current management approach. We further identified 114 measures, grouped into six strategies to meet such requirement. We conclude that a sole focus on technical fixes in flood management is insufficient under rapid environmental changes. Instead, integrating alternative measures combined with suitable governance and institutional settings offer great opportunities to minimize flood risk under climate change and accelerating developments. Findings from this study show how to overcome several profound challenges in contemporary flood risk management in one of the world's most vulnerable river deltas.

The manuscript corresponding to this chapter is currently under review.

5.1. Introduction

Annual floods in the Vietnamese Mekong River Delta not only bring great benefits for local inhabitants and the regional economy but also constitute a major safety risk (Hoa et al. 2008; MDP 2013). Located in the downstream reach of the Mekong River (Figure 5.1), the Mekong River Delta (hereafter, the Mekong Delta) receives about 475 km^3 of upstream inflow annually (MRC, 2005). About 70% to 80% of this amount comes during the wet season (July-December), causing widespread flooding across the floodplains. Floodwater, especially the overland water flow, generates multiple benefits for natural ecosystems, fisheries and agriculture (Costa-Cabral et al. 2008; Arias et al. 2013; Chapman et al. 2016). These benefits include providing migration routes and breeding sites for fish species, distributing nutrient-rich sediment for agriculture, recharging ground water aquifers and controlling sea-water intrusion. Despite these abundant benefits, extreme floods also cause losses of human lives and severe damages to crops and infrastructures (Västilä, 2010, Tri et al. 2012). For example, the historic flood in 2000, a 50-year flood with estimated economic losses of over US$ 200 million, illustrates the delta's high vulnerability to extreme floods (Cosslett and Cosslett, 2014). Given the valuable benefits and severe flood damages, flood management in the Mekong Delta requires effectively controlling excessive floodwater without compromising the flood benefits and other development objectives (Käkönen, 2008; Pham, 2011).

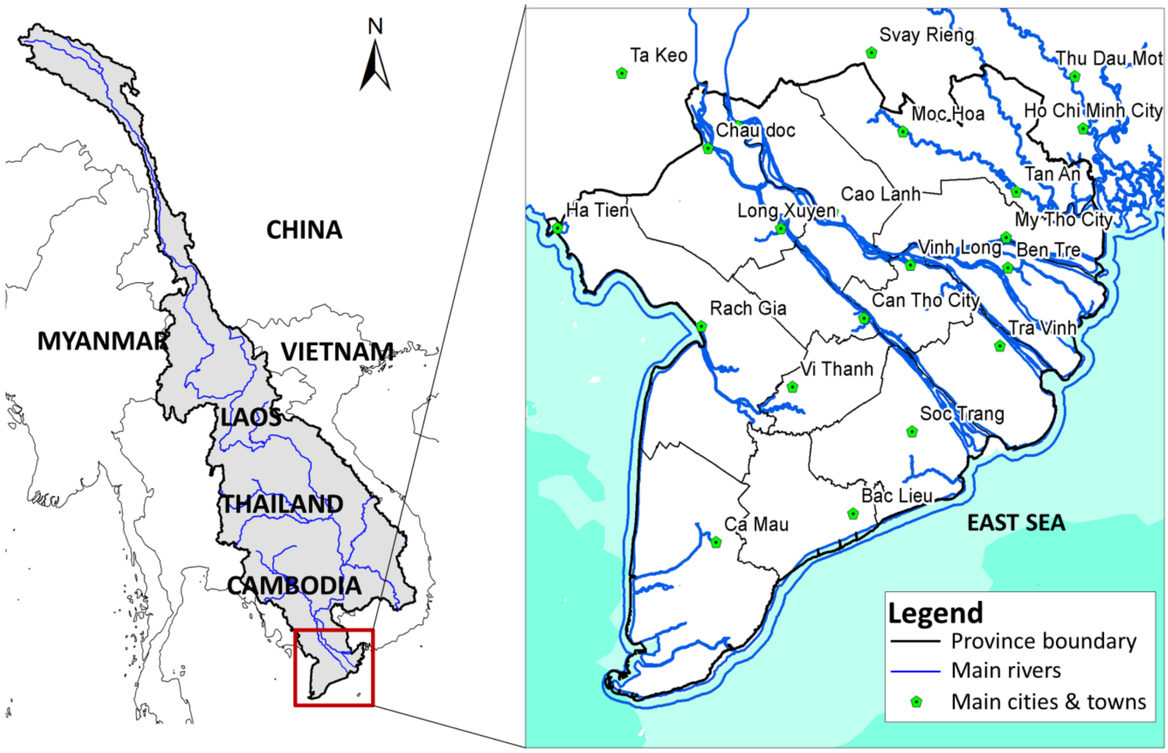

Figure 5.1 Overview maps of the Mekong River Basin (left) and the Mekong Delta (right)

Flood management in the Mekong Delta, however, is facing critical challenges caused by climate change and accelerating socioeconomic developments (MDP 2013). Flood hazards are projected to increase substantially under future climate change due to higher upstream inflow and downstream sea-level rise (Wassmann et al. 2004; Hoang et al. 2016). These increasing flood hazards are expected to exceed the delta's current coping capacity and thus constitute a major threat for safety and sustainable development (Thanh et al. 2004; Wassmann et al. 2004). Furthermore, prevalent uncertainties in the future flood hazards also hamper long-term planning and investments for flood management (MDP, 2013; Trung & Thanh, 2013). Accelerating socioeconomic developments including economic and population growth, land-use change and infrastructural developments (e.g. building dikes and hydropower dams) also introduces new management challenges. Challenges are defined here as factors or processes that can hinder successful planning and implementation of flood management activities.

Since the launch of the "Doi Moi" policy (Pham, 2011) during the early 1990s, the delta's economic structure has developed from a rice-based economy toward a more diversified system with growing contributions from fishery, aquaculture, horticulture, services, trade and industry. This diversified economy requires pursuing multiple, sometimes competing, flood management objectives (Käkönen, 2008; Renaud and Kuenzer, 2012). Reflecting on these objectives, Käkönen (2008) and Pham (2011) questioned the suitability of the current technological-centric flood management approach to spontaneously secure flood safety and sustain flood benefits. This and other challenges experienced in flood management were also reported in recent literature, including technical difficulties (Hoa et al. 2008; MDP 2013), limited resources and capacity (Bastakoti et al. 2014; Hoa et al. 2014a), and governance and institutional constraints (Waibel et al. 2012; MDP, 2013). Without timely solutions, the challenges can hamper flood management efforts and thereby creating serious consequences for the people and the economy of the Mekong Delta (MDP 2013).

Recent studies, however, paid little attention to identify and address the challenges for flood management. In many cases, emphasis is still placed on finding the 'right' technical measures, following the conventional flood management approach (Lebel and Sinh, 2009; Marchand et al. 2014). As a result, the questions of which challenges are critical and how to effectively overcome them remain largely unaddressed. Additionally, little is known about how existing challenges manifest and whether new challenges arise due to climate change and socioeconomic developments. These important knowledge gaps need to be addressed to effectively inform and support flood management in the Mekong Delta.

This study therefore aims to (i) systematically identify key challenges for flood management in the contexts of climate change and accelerating socioeconomic developments, and (ii) develop intervention measures and strategies to adequately address these challenges for the Mekong Delta. We collected data using systematic literature review and expert surveys (Sections 5.2.1 and 5.2.2). Using statistical inferences and qualitative data analysis techniques (Section 5.2.3), we identify and analyse a diverse set of flood management challenges (Section 5.3.2). Furthermore, we present 114 identified measures and six thematic strategies to address the challenges (Section 5.3.3). In Section 5.3.4, we describe how the strategies and measures are tailored to the challenges as guidance for implementation. Section 5.4 discusses the results, implications for flood management and Section 5.5 concludes.

5.2. Methodology

5.2.1. Systematic literature review

We used systematic review methods (Ford et al. 2015; Biesbroek et al. 2013) to collect and analyse all relevant peer reviewed literature using the ISI Web of Science Database. The database search used "Mekong", "Delta" and "flood" as keywords and this query returned 133 entries, from which we selected 86 documents and excluded 47 irrelevant documents (based on their titles). We were also interested in other relevant documents that are not available in this database. These include policy and planning documents and those published in Vietnamese. We contacted our research networks to query and retrieve 19 additional documents. In total, the literature search yielded 105 documents, which were then subjected to a detailed screening procedure. This further eliminated 52 documents, because they either did not cover our study area, or did not relate to the food management topic. The complete procedure resulted in 53 relevant documents, which were included into the detailed literature review and analyses.

In this detailed review, we structured relevant information from the collected documents into separate sections. For each document, we extracted information on: (1) Generic information (authors, publication year, publication type, topic and geographical coverage); (2) Flood management challenges (further classified into Group I - technical, Group II - institutional and governance, and Group III - resources and capacity challenges), and (3) current flood management practices, see Supplementary information E (Systematic literature review of flood management in the Mekong Delta) for the results.

5.2.2. Expert survey

On top of the literature review, we developed a questionnaire survey (Biesbroek et al. 2011) to collect insights from relevant experts about two key questions, namely: (1) What do they consider to be the key challenges for flood management in the Mekong Delta?;

and (2) What do they consider as the solutions (i.e. the measures) to overcome these challenges? The survey (Supplementary information F) combines multiple-choice and open-ended questions to collect information about flood management challenges, potential measures and the experts' professional backgrounds.

The survey is self-administrated and is implemented onto an online survey platform (LimeSurvey, 2015). Survey respondents were identified from the authors' research networks, contact information found in relevant literature and secondary referring (i.e. respondents introduce new experts who they think suitable for the survey). The online survey strategy helps effectively targeting many respondents within reasonable survey administration time. Also, this strategy is especially useful when our targeting respondents spread out in different locations (Kumar, 2005). In total, the survey invitation was sent to 132 experts by email in May 2015, followed by two reminders sent after two or four weeks, respectively.

5.2.3. Data analysis

We used both quantitative and qualitative data analysis techniques to gain insights about various aspects, including the literature profile, expert sample, flood management challenges, measures, and strategies. We first analysed the compositional characteristics of the literature and the expert sample by calculating standard descriptive statistics (i.e. sums, means and percentages). The literature composition was characterized by topics, focal spatial levels and publication types. We calculated the expert sample's composition by professional occupations, focal flood management aspects, and working levels.

We ranked the challenges by their important levels, which were calculated as aggregated and group-wise means of the individual rankings. We also checked the linkages between the individual challenges by calculating correlation coefficients between the challenges' rankings. Additionally, we used multivariate regression to investigate how the respondents' backgrounds (e.g. occupations, working levels and working focuses) influence their judgements about the challenges' importance (Hoa et al. 2014b).

We further developed measures and strategies to address flood management challenges by conducting content analysis of the respondents' open-ended recommendations (Biesbroek et al. 2011; Kumar 2005). The measures were identified from the recommendations through open-coding technique, using Atlas-ti-v7 software. During open-coding, the respondents' recommendations were summarized and systematically assigned to a set of codes (i.e. the codebook) where each code represents a flood management measure. The codebook was cross-validated following Kumar (2005). The coding procedure was quality-checked by comparing the measures sets derived from two independent codebooks conducted by two of the authors. After this, we combined individual measures based on their objectives to develop thematic flood management strategies. Lastly, we calculated the recommendation rates (i.e. how many times a strategy is recommended for a challenge) to gain insights about how the strategies are tailored to different challenges according to the experts.

5.3. Results

5.3.1. Reviewed literature, expert sample and current flood management practices

Literature profile

Focal topics, focal spatial levels and publication types of the reviewed literature are summarized in Figure 5.2. The total 53 documents (Supplementary information E) consist of 21 peer-reviewed scientific articles, 5 book chapters, 25 reports and 2 planning and policy documents. Topic-wise, the literature exhibits relatively equal coverages of different flood management aspects. Flood modelling, monitoring and early warning topic shows the highest coverage (n=23) while building flood resilience topic shows the lowest coverage (n=12). Regarding spatial levels, a majority (n=39) of the documents focuses on the delta-wide level. Flood management at the sub-delta levels (i.e. regional, provincial, local and individual households), however, receives less attention, shown by markedly fewer documents.

Expert sample

In total, 71 out of 132 invited experts completed the survey. They consist of 14 government officers, 13 NGO officers or consultants, 22 natural scientists, 13 social scientists, 7 engineers and 2 experts had other occupations. The experts work at different spatial levels, ranging from local and provincial (n=15), delta-wide (n=27), to national (n=11) and international (n=18). They work on various flood-relating topics, including flood research (n=14), water management and planning (n=18), land use management and planning (n=5), flood protection (n=2), building flood resilience (n=12), and climate change impact and adaptation (n=12). About one-third of the experts (i.e. 21 out of 71) listed flood as the central focus of their professional practices. Overall, the expert sample shows relatively good representations of both spatial levels and flood management aspects.

Current flood management practices

We identified from literature a variety of flood management measures currently practiced in the Mekong Delta, ranging from infrastructural to technical to regulatory measures. The predominant approach is flood control and flood prevention using infrastructural measures (MDP 2013; Marchand et al. 2014). In particular, the floodwater levels and flood extents are controlled by using drainage systems, floodwater discharge canals, sluice gates and protection dikes. High dikes are used to protect residential areas and the main agricultural zones, while the secondary dikes protect crops against moderate floodwater levels at the beginning of the flood season. Regarding infrastructural measures, the survey results also show that experts expressed their preferences for several options for flood protection, including (i) full flood control for urban areas; (ii) controlled flooding for agricultural zones; (iii) natural floodplains restoration; and (iv) increasing flood discharge capacity. Next to infrastructural measures, different technical measures are also available from the literature. The main technical measures are monitoring, forecasting and early warning, flood emergency response plans, communication and awareness raising (Hoa et al. 2014a; Trung et al. 2013). Lastly, several regulatory measures exist, including relocation from flood-prone zones, adaptation to flood and developing flood management legislations (Pham 2011). Flood management measures are implemented at different spatial levels ranging from local, household actions to delta-wide flood management programs.

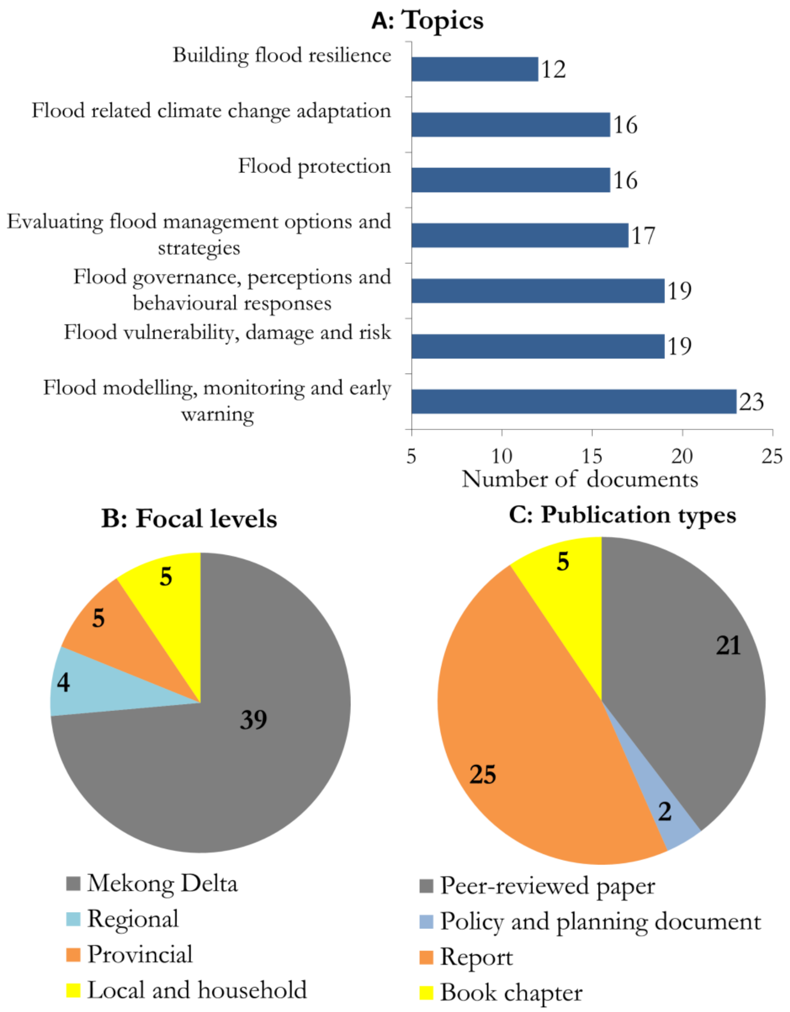

Figure 5.2 Compositional profile of the reviewed literature

5.3.2. Flood management challenges

We identified 19 flood management challenges (C1 to C19) from the literature (Table 5.1). These challenges are diverse and relate to different flood management aspects. These were grouped (G1 to G3) into G1 - Technical challenges (C1 to C7); G2 - Governance and institutional challenges (C8 to C13); and G3 - Resources and capacity challenges (C14 to C19). Group G1 (i.e. technical challenges) is reported more often in the literature compared to the other groups, shown by a higher number of challenges and more reporting documents. The more frequently reported challenges in this group include "C1 - Lack of knowledge and understandings about the flood mechanisms in the floodplain "; "C2 - Existing flood protection measures create unwanted impacts"; "C4 - Research results are not taken up in flood management" and "C7 - Uncertainties in future climate change, sea-level rise and socioeconomic development hinder development of flood management plans". Common flood management challenges that related to the governance and institutional settings (Group G2) were also reported, resulting the following main challenges: "C9 - Limited coordination and collaboration in flood management across provinces and districts" and "C10 - Conflicting interests between different management departments and regions". Group G3 consists of those challenges related to resources and capacity for flood management. The commonly reported challenges in this group are "C14 - Flood management lacks financial resource" and "C18 - Lack of data and equipment for flood risk management". We further found that flood management challenges in the Mekong Delta tend to relate to each other, shown by relatively high correlation coefficients between individual challenges (see Supplementary information G - Correlation coefficients between the challenges' rankings). The strongest correlating challenges include C5, C9, C11, C15 and C19. These strong correlations suggest that the challenges exhibit intricate interlinkages and that they are often experienced together rather than individually in practice.

The survey results further show that flood management in the Mekong Delta faces multiple critical challenges (Figure 5.3). A majority of these challenges (12 out of 19) was considered important by the experts. Furthermore, 89% of the experts indicated that flood management has become more challenging comparing to three decades ago and they attribute the reasons to population growth (77%), dikes construction (70%), land use change (68%), hydropower dams construction (68%), climate change (62%) and sea level rise (54%). Additionally, the challenges' rankings by the experts clearly indicated which challenges were considered more important (Figure 5.3). The Top-5 challenges according to all experts were: C2 - Existing flood protection measures create unwanted impacts; C8 - Some factors causing flood are outside management boundary, i.e. in other country, province or district; C9 - Limited coordination and collaboration in flood management across provinces and districts; C10 - Conflicting interests between different management departments and regions; and C13 - Flood management system is not responsive to new issues and challenges. Notably, four out of the Top-5 challenges belong to group G2 - governance and institutional challenges, making this group the most predominant one compared to the other groups. These challenges were consistently reported by experts from all occupations, working levels and working focuses, suggesting that they are commonly experienced across multiple spatial levels and at different aspects of flood management.

Table 5.1 Flood management challenges in the Mekong Delta as reported in literature. More details about the challenges and reporting literature is available in Supplementary information E.

	Challenges	Reporting literature[1]
G1	**Technical challenges**	
C1	Lack of knowledge and understandings about the flood mechanisms in the floodplain	1-4; 8-13; 15-19; 24; 25; 28; 29; 32; 33; 36; 37; 42; 43; 45; 47; 48; 50
C2	Existing flood protection measures create unwanted impacts	3; 9; 16-18; 20; 29; 32; 34; 35; 38; 41; 43; 47; 49-51
C3	Flood forecasting and early warning systems are not effective and reliable	7; 12; 14; 15; 31; 42; 51
C4	Research results are not taken up in flood management	14; 15; 31; 34; 35; 37; 42; 44
C5	Local, indigenous knowledge is underused in flood management	7; 14; 15; 22; 23; 35
C6	Suitable strategies and measures for flood management are not available	1; 12; 14; 15; 31; 32; 34; 46; 52; 53
C7	Uncertainties in future climate change, sea-level rise and socioeconomic development hinder development of flood management plans	1-3; 8; 11-13; 15; 18; 31; 33; 36; 37; 48
G2	**Governance and institutional challenges**	
C8	Some factors causing flood are outside management boundary, i.e. in other country, province or district	1, 5, 9, 32, 34, 45
C9	Limited coordination and collaboration in flood management across provinces and districts	1, 4, 5, 6, 7, 9, 17, 25, 26, 34, 40, 42, 51, 53
C10	Conflicting interests between different management departments and regions	7, 9, 23, 31, 32, 40, 43, 45, 48, 49
C11	Flood and water management plans at different levels are inconsistent, causing difficulties in implementation	7, 9, 33, 48
C12	Top-down, centralised approach to flood management	6, 7, 9, 35, 40, 48
C13	Flood management system is not responsive to new issues and challenges	9, 15, 25, 31
G3	**Resource and capacity challenges**	
C14	Flood management lacks financial resource	1; 5; 9; 14-16; 25; 27; 28; 31; 35; 42; 46; 53
C15	Finance for flood management does not reach relevant regions and stakeholders	6; 16; 27; 28; 42; 53
C16	Flood management staffs lack important capacities	9; 15; 31; 33; 34; 40
C17	Insufficient number of staffs for flood management	9, 40
C18	Lack of data and equipment for flood risk management	2; 4; 7; 10; 12; 16-18; 21; 25; 28; 30; 37; 39; 42; 45
C19	Lack of legislative and institutional capacities for flood management	5; 6; 17; 34; 40; 42-44

[1]*Numbers correspond to the reviewed documents listed in Supplementary information E.*

			Occupation						Spatial level				Working focus						
		All respondents	Government officers	NGO & consultants	Natural scientists	Social scientists	Engineers	Other occupations	International	National	Mekong Delta	Provincial & local	Flood research	Water man. & planning	Land use man. & planning	Flood protection	Flood resilience	Climate impact & adaptation	Other working focuses
Technical	**C1**	**3.96**	4.14	3.85	4.18	3.38	4.14	**4**	3.83	4.18	4	3.87	**4.5**	3.78	3.6	3	4	4.08	3.57
	C2	**4.21**	**4.36**	**4.15**	**4.23**	**4.31**	3.86	**4**	4.06	**4.27**	**4.22**	**4.33**	4.21	**4.11**	4	**4**	**4.33**	4.38	**4.14**
	C3	**4**	**4.36**	4	3.95	3.92	3.71	3.5	3.78	**4.36**	3.85	4.27	4.14	4	3.8	3.5	3.92	3.92	**4.29**
	C4	**3.79**	3.64	3.77	3.73	4.08	3.71	**4**	3.89	3.36	3.89	3.8	3.93	3.67	4	3.5	3.83	4.08	3.14
	C5	**3.76**	3.71	3.85	3.73	3.85	3.71	3.5	3.89	3.64	3.67	3.87	3.64	3.72	3.8	3	3.75	3.92	4
	C6	**4.03**	4.07	4.08	3.95	4.08	4.14	3.5	**4.28**	3.73	3.96	4.07	3.93	**4.11**	3.8	**4**	3.92	4.23	4
	C7	**4.06**	3.79	4.08	3.95	**4.38**	**4.43**	3.5	4.11	4	3.96	4.2	3.86	3.89	**4.2**	**4**	3.67	**4.77**	**4.14**
Governance & institutional	**C8**	**4.24**	**4.36**	4.08	4.14	**4.31**	**4.29**	**5**	4.17	4	**4.22**	**4.53**	4.29	3.89	4	**5**	**4.5**	**4.46**	**4.14**
	C9	**4.44**	4	**4.31**	**4.59**	**4.62**	**4.57**	**5**	**4.67**	4.18	**4.41**	**4.4**	**4.43**	**4.5**	**4.6**	3	**4.17**	**4.69**	**4.57**
	C10	**4.46**	4.14	**4.38**	**4.59**	**4.69**	**4.43**	**4.5**	**4.61**	4.18	**4.52**	**4.4**	**4.36**	**4.5**	**4.8**	3.5	**4.5**	**4.54**	**4.43**
	C11	**4.2**	4.21	**4.23**	**4.23**	4.15	4.14	**4**	**4.28**	**4.27**	**4.19**	4.07	**4.36**	**4.17**	**4.2**	3	4.08	**4.46**	4
	C12	**4.01**	3.86	3.92	4.14	4.08	**4.29**	**3**	**4.28**	3.73	4.04	3.87	4.07	**4.11**	3.6	**4**	**4.25**	3.77	4
	C13	**4.27**	**4.36**	**4.23**	**4.32**	4.15	**4.29**	**4**	4.17	**4.55**	4.07	**4.53**	**4.43**	**4.11**	**4.2**	**4**	**4**	**4.62**	**4.29**
Resources & capacity	**C14**	**3.93**	**4.5**	3.92	3.86	3.46	4.14	3	3.89	4.18	3.85	3.93	4.07	**4.17**	4	3.5	3.92	3.62	3.71
	C15	**3.8**	3.86	3.77	3.77	3.92	3.57	**4**	4.06	3.73	3.67	3.8	3.79	3.83	4	3	3.83	3.77	3.86
	C16	**4.04**	4.29	4	4.14	3.69	4.14	3.5	3.94	**4.27**	3.96	4.13	4.29	3.83	**4.4**	**4**	3.83	4.15	4
	C17	**3.56**	3.79	3.62	3.55	3.38	3.57	3	3.56	3.82	3.44	3.6	3.79	3.44	3.2	3.5	3.58	3.62	3.57
	C18	**4.01**	4.21	4.08	4.14	3.69	3.86	3.5	4.17	3.91	3.89	4.13	4	4.06	4	3	4.08	4	**4.14**
	C19	**3.96**	4.21	3.85	3.86	4	3.71	**4.5**	4.06	4	3.7	4.27	3.86	4	4	3.5	4	4.08	3.86

Figure 5.3 Ranking importance of flood management challenges (aggregated and per groups). Higher scores indicate more important challenges; the Top-5 challenges in each group are highlighted. C1 to C19 refers to the challenges listed in Table 5.1

Some specific challenges (e.g. C2, C6, and C11) are found to manifest differently at multiple spatial levels, shown by their different important rankings across local, provincial, Mekong Delta, national and international levels. For example, the unwanted impacts of the current flood protection dikes (C2) were seen more important at the provincial and local levels. The dikes' impacts, however, appeared less critical at the higher spatial levels, i.e. the Mekong Delta, national and international levels. Similarly, while challenge C11 (i.e. inconsistencies in planning) was considered important at the national and international levels, this challenges was regarded as less important at the provincial and local levels.

We also found that certain challenges are rather specific to the experts' backgrounds, especially their occupations. Our multivariate regression results show that the rankings of several challenges (e.g. C2; C12; C13; C14; and C17) were dependent upon the expert's occupation. For instance, the expert group of engineers did not consider the negative dike impacts (C2) as important, while all other groups regarded this challenge as a critical issue in the Mekong Delta. Differentiated rankings across the expert groups were also observed for C6 (lack of strategies and measures for flood management). Several respondent groups (i.e. engineers, internationally active experts and those working on water management and planning) regarded this challenge as highly important, whereas some other groups (i.e. those working at the national and Mekong Delta levels and natural scientists) did not see this as a critical issue. We further discuss the implications of the challenge's specificities to spatial levels and expert groups in the discussion section.

5.3.3. Measures and strategies to address flood management challenges

Table 5.2 Main measures to address the Top-5 flood management challenges

Top challenges	Important rank	Ranking score	Measures
C10 Conflicting interests between different management departments and regions	1st	4.46	▪ Promote integrated management ▪ Promote multi-objective flood management ▪ Implement integrated flood impact assessment ▪ Improve data sharing ▪ Improve collaboration between actors
C9 Limited coordination and collaboration in flood management across provinces and districts	2nd	4.44	▪ Develop coordinating board ▪ Improve collaboration between actors ▪ Promote exchange and learning ▪ Promote multi-level management ▪ Improve data sharing
C13 Flood management system is not responsive to new issues and challenges	3rd	4.27	▪ Shift thinking and management paradigm ▪ Set priorities in management ▪ Improve communication ▪ Build capacity for flood management staffs ▪ Improve knowledge uptake
C8 Some factors causing flood are outside management boundary, i.e. in other country, province or district	4th	4.24	▪ Improve collaboration between regions ▪ Improve collaboration between actors ▪ Improve communication ▪ Promote exchange and learning ▪ Implement integrated flood impact assessment
C2 Existing flood protection measures create unwanted impacts	5th	4.21	▪ Revise existing measures ▪ Develop new technical measures ▪ Address unwanted impacts of existing measures ▪ Optimize existing control infrastructures ▪ Promote integrated planning

Experts identified 114 measures (Supplementary information H: Measures to address flood management challenges) to address flood management challenges in the Mekong Delta. Overall, the measures are diverse, ranging from technical interventions (e.g. improve flood monitoring and early warnings) to improving collaboration and promoting integrated flood management. Certain measures are recommended more often by the experts and this suggests a higher priority for implementation. The most frequently recommended measures include "Promote exchange and learning", "Implement integrated flood impacts assessment", "Improve collaboration between stakeholders", "Improve communication", and "Build capacity for flood management staffs". Notably, the measures targets specific challenges, resulting in specific sets of measures for each particular challenge. The sets of main measures for the Top-5 challenges are presented in Table 5.2.

We further constructed six thematic strategies to address flood management challenges by grouping the individual measures based on their objectives. Below the strategies are described together with their main measures. The list of strategies and their associated measures is provided in Supplementary information I (Flood management strategies and associated measures).

Strategy S1: Create an enabling environment for flood management

A more enabling environment for flood management in the Mekong Delta entails three clusters of measures. Firstly, the experts recommend a more participatory and inclusive flood management environment, where stakeholders can affectively participate in the management process. Representative measures within this cluster include promoting participatory approaches and supporting stakeholder's negotiation. The second cluster of measures targets limited coordination in flood management. Here, improvements are needed for both cross-regional and between-stakeholders coordination. In response to the currently limited management coordination, many experts suggest establishing a coordinating board at the delta level. Lastly, resolving the current management bottlenecks constitutes the third measure cluster, with specific measures such as resolving conflicts; developing agreements and common understanding between stakeholders; and improving transparency in flood management.

Strategy S2: Strengthen and diversify the flood management portfolio

Overall, strategy S2 aims at developing a better flood management portfolio. Such portfolio is configured of multiple measures which together ensure that flood management practices are (1) better integrated; (2) better tailored to the local contexts; and (3) more diverse. Commonly suggested measures to pursue integrated flood management are promoting integrated flood management approaches; adapting multi-objective flood management; and combining multiple measures in planning and implementation. Tailoring flood management measures to the local context, on the other hand, can be achieved by localizing management processes, applying local knowledge and considering local conditions and resources availability when implementing the measures. Lastly, the experts suggest diversifying the current management portfolio with specific measures including exploring flood benefits; using complementary measures to resolve unwanted impacts of implemented measures; and developing non-regret and adaptive measures.

Strategy S3: Foster cross-boundary interactions

Strategy S3 is characterized by two main themes, namely collaboration; and exchange and learning. Experts strongly emphasize improving collaborations, both across regions and between different stakeholders. Regarding the spatial aspect, inter-provincial collaboration through joint projects and data sharing is a frequently recommended measure. Additionally, collaboration with upstream countries in the Mekong river basin is also often suggested, with specific measures including participating in international forums; and improving the Mekong River Commission's role in coordinating international dialogues and negotiations. The second aspect of cross-boundary interactions focuses on "Promoting exchanges and learning", where specific measures include organizing workshops, benefiting from international expertise and sharing experiences with similar river deltas. Overall, improved exchange and learning are recommended both within the Mekong Delta and at the international level.

Strategy S4: Improve capacity and resources

Improvements in capacity and resources for flood management are mostly recommended by improving financial and human resources. Besides a higher share of state budget for flood management, experts consider it to be necessary to diversify the financial resources through several specific measures including combining loan and grant in project funding; generating funding through international collaboration; and attracting investment from the private sector. Regarding human resources, specialized training and education is strongly emphasized as a main measure to improve staff's expertise and skills. Additionally, improving recruitment effectiveness and better employment conditions are also regarded as suitable measures. Lastly, optimization of resources use in flood management is also recommended frequently. In particular, optimization is suggested through better matching available finance to the planned action, and matching flood management problems to suitable expertise.

Strategy S5: Improve data and decision support

Strategy S5 consists of three measure clusters to improve data and decision support, namely supporting anticipatory flood management; addressing knowledge gaps and evaluating flood management measures. Firstly, experts commonly recommended anticipatory management based on effective and reliable data and decision support services. Specific improvements include improving flood monitoring; improving flood modelling; and developing effective forecasting and early warning systems. Furthermore, the experts also suggest to better synchronize data and to effectively deliver forecasting data to relevant users and regions. The second measure cluster focuses on addressing knowledge gaps through collecting more data and implementing integrated flood impact assessment. Regarding flood impact assessment, experts frequently focus on the impacts of hydropower dams along the Mekong's mainstream on downstream flood hazard. The last measure cluster consists of two main measures, namely testing measures before implementation and comparing different measures for implementation.

Strategy S6: Innovate and shift flood management approaches

Strategy S6 focuses on changes in flood management approaches at both operational and strategic levels. At the operational level, this strategy entails developing new technical measures and adapting current policies to better support flood management. Regarding new technical measures, the experts often suggest restoring the natural floodplains and developing flexible flood protection dikes to effectively distribute the flood water across the delta. At the strategic level, shifting the thinking and management paradigm is also often recommended. In particular, the experts suggest shifting from the conventional preventing and controlling approach toward integrated flood management using more diverse combinations of protection dikes with flood-resilience land-uses and livelihoods.

5.3.4. Tailoring strategies and measures to flood management challenges

The strategies and measures are tailored differently to individual flood management challenges. This tailoring is illustrated by different recommendation rates at which the strategies and measures are recommended for the challenges, both individually and per group (Figure 5.4). The recommendation patterns shown in Figure 5.4 provide useful insights about how the strategies and their associated measures can be best tailored to the challenges. First, the strategies exhibits varying recommendation rates per challenges, implying that they target specific challenges while appear less applicable to others. For example, strategy S1 - Create an enabling environment mostly addresses challenges under the "Governance and institution" challenges group. Similarly, strategy S2 - Enrich and strengthen the flood management portfolio highly focuses on "Technical" challenges, especially challenge C2 (i.e. unwanted impacts of existing flood protection measures).

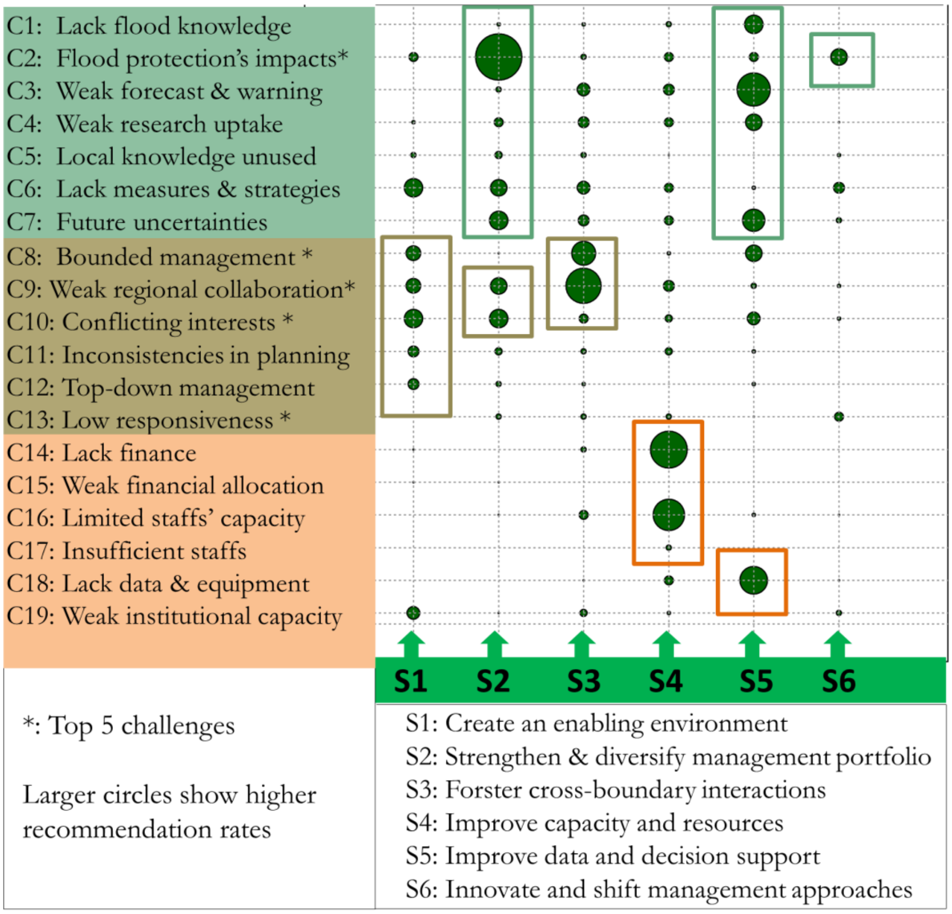

Figure 5.4 Tailored strategies (S1-S6) to flood management challenges (C1-C19) based on expert survey. Full challenges' description is available in Table 5.1

Secondly, addressing the challenges often requires combining multiple strategies and measures. All challenges in the Top-3 list (i.e. C8, C9 and C10) exhibit this feature, where they are all addressed with multiple strategies (Figure 5.4). The combined strategy notion also applies to the challenge groups (i.e. technical; governance and institutional; and resources and capacity groups), where each group is tailored with multiple strategies. In particular, three strategies (i.e. S2, S5 and S6) are recommended for the technical challenges group. The most important challenge in this group (i.e. C2 - Existing flood protection measures create unwanted impacts) are tailored with S2 - Enrich and strengthen flood management portfolio and S6 - Innovate and shift approaches. Similarly, the group of governance and institution challenges mostly require measures under strategy S1 - Create an enabling environment, strategy S2 - Enrich and strengthen flood management portfolio and strategy S3 - Foster cross-boundary interactions. For example, challenge C9 - Limited coordination and collaboration in flood management across provinces and districts are tailored with "Develop a coordinating board for flood management", "Promote exchange and learning" and "Improve collaboration between stakeholders". Lastly, many measures under the strategies S4 and S5 are regarded as relevant to address the group of resources and capacity challenges. Typical measures for this challenge group include "Build capacity for flood management staff", "Improve data sharing" and "Diversify funding sources".

5.4. Discussion

We identified 19 challenges for flood risk management in the Mekong Delta. About two-third of these challenges are considered important by the expert panel, further confirming that flood risk constitutes a major threat to water-related safety (MPD, 2013; Hoang et al. 2016). While many previous studies (Hoa et al. 2008; Kubiszewski et al. 2013; Piman et al. 2013) highlighted technical difficulties, this study found that many critical challenges arise from the current governance and institutional settings. Our result showed that experts considered governance and institutional challenges more important than the technical, resource and capacity challenges. In the Mekong Delta, the strong focus on technical challenges is a logical reflection of the current technological-centric flood management approach. This approach, however, has become insufficient under the changing climate and accelerating socioeconomic developments, as suggested by the results from our survey as well as those from other studies, including Käkönen (2008), Pham (2011), and Marchand et al. (2014). The existing governance and institutional settings have constrained the adoption of both 'hard' and 'soft' flood risk management measures that are deemed necessary to transform parts of the current flood risk management approach to effectively deal with future risks . This technical management approach, which is the result of path dependency caused by many past (investment) decisions, has probably created strong preferences over flood management practices being implemented in the Mekong Delta. Additionally, the existing governance and institutional settings reinforce vested interests of actors and incentivize them to reinforce the status quo (Bachrach and Baratz, 1970). This makes transformational changes (Kates 2012) even more challenging, especially when these changes in the flood risk management system should be fast, large scale and deep at the same time (Termeer et al. 2016). Our findings are not limited to the Vietnamese Mekong Delta, as other studies in Asia also found similar issues emanating from the existing governance and institutional settings, including in Nepal (Dixit 2003) and Thailand (Lebel et al. 2011).

We further identified 114 measures for flood management and grouped them into six thematic strategies. The quantity and diversity of the measures reflect a complex flood management landscape in the Mekong Delta, which is frequently reported in the current literature (Birkmann et al. 2012; MDP, 2013). Additionally, while the challenges for flood management were relatively well documented in recent studies, few have developed the intervention measures and strategies towards eventually overcoming these challenges. Next to 'hard' technical interventions that are frequently found in the literature, our study identified many 'soft' measures to adequately account for the most critical group of governance and institutional challenges. We found that this mix of different measures is important to address multiple, interconnected challenges being experienced in the Mekong Delta.

Finally, we provide several recommendations for flood risk management based on our findings. First, we recommend combining the strategies and measures for implementation rather than deploying them individually. While this seems self-evident, flood risks measures are implemented in isolation and consequently face the challenge of becoming maladaptive, or create new challenges elsewhere (Lebel and Sinh, 2009; Chapman et al. 2016). To effectuate transformational changes requires a more holistic approach that cannot be achieved by looking at individual challenges or implementing technical fixes in isolation. As most flood risk challenges are co-occurring and intractably interlinked, they need to be simultaneously addressed to consider possible trade-offs. Second, given the challenges' different manifestations across different spatial levels, adapting the strategies and measures to the regional contexts is highly important for successful implementation. The identified challenges and measures found in this study probably require further specification to operationalise and implement them. One possibility to do this is to organize stakeholder workshops to develop measure packages, targeting specific sets of challenges. Such approach can be useful to develop local flood management measures that are relevant to the specific challenges and stakeholders' needs.

5.5. Conclusion

Effective flood risk management is a top priority in the Mekong Delta, however, this process is increasingly challenged by climate change and accelerating socioeconomic developments. This is one of the first studies to systematically identify key challenges and to develop tailored intervention measures and strategies. We found that the identified challenges are diverse and multifaceted; however, many critical challenges predominantly arise from the current governance and institutional settings. The identified mismatch between this predominant type of challenges versus the currently implemented technical measures has important implications for management. Minimizing flood risk under such circumstance requires adapting the current flood management system to better account for the key challenges, thus minimizing flood risk. In this study, we have identified six strategies to meet such requirement, namely (S1) Create a more enabling environment for flood management; (S2) Strengthen and diversify the flood management portfolio; (S3) Foster cross-boundary interactions; (S4) Improve capacity and resources; (S5) Improve data and decision support; and (S6) Innovate and shift flood management approaches. These strategies and their associated measures contribute to the emerging repertoire of interventions in the literature to deal with some of the profound challenges in contemporary flood risk management. We conclude that a sole focus on technical fixes will be insufficient for flood risk management in the Mekong Delta under rapid environmental changes. Instead, integrating alternative measures combined with suitable governance and institutional settings offers great opportunities to minimize flood risk in views of both climate change and accelerating socioeconomic developments.

CHAPTER 6

Synthesis

6.1. Introduction

The Mekong River's flows and water resources are of great values for six national economies, a growing population of 70 million people, and unique, highly biodiverse ecosystems. This international river, however, also represents one of the world's major hotspots in terms of increasing human pressures on water resources and climate-change vulnerability. Despite stronger research focus and a growing scientific knowledge body, prevalent uncertainties exists about how the Mekong's future flow regime and hydrological extremes will change under climate change and accelerating socioeconomic development including irrigation expansions and hydropower developments (Kingston et al. 2011; Lauri et al. 2012; Piman et al. 2013). Additionally, effective adaptation measures and strategies are poorly developed despite critical vulnerabilities to future hydrological changes (Keskinen et al. 2010; MDP, 2013; Bastakoti et al. 2014). This study addresses these knowledge gaps through achieving two research objectives:

1. *To quantify future hydrological changes (both flow regimes and hydrological extremes) in the Mekong basin; and*
2. *To develop measures and strategies to adapt to the projected hydrological changes.*

These research objectives were achieved through a multidisciplinary methodological framework, following the four-step procedure described below.

First, a hydrological impact assessment was implemented to quantify climate change impacts on the Mekong River flows and hydrological extremes (Chapter 2). Climate data from five global climate models (GCMs), two RCPs (i.e. RCP4.5 and RCP8.5) were statistically downscaled and bias corrected to simulate river flows using the VMod hydrological model (Lauri et al. 2006). Given prevailing uncertainties in hydrological impact signals reported in earlier studies (Kingston et al. 2011; Thompson et al. 2013) this study used the most recent CMIP5 climate scenarios (Taylor et al. 2012) and assessed whether the derived impact signals are more robust. Additionally, we focused strongly on future changes in the high and low flow conditions to address an important knowledge gap about hydrological extremes under climate change in the Mekong basin.

Second, a scenario-based hydrological impact assessment was implemented to assess future changes in the Mekong's flow regime under the combined impacts of climate change and main basin-wide development activities. Although the Mekong's future flows are likely driven by multiple driving factors, or drivers, (Keskinen et al. 2010; Lauri et al. 2012), a majority of current studies focuses solely on climate change impacts. As a result, little is known about hydrological changes under multiple driving factors and socioeconomic development in particular. A newly developed crop and irrigation module, and a hydropower dam operation module were coupled into the VMod model to simulate river flows under the combined impacts of climate change, irrigation expansions and hydropower developments. This study therefore not only characterized the complex mechanisms of future hydrological changes but also showed critical changes that likely affect safety risk, economic activities and the Mekong's unique aquatic ecosystems.

Third, the study zoomed in on the Mekong Delta as a critical vulnerability hotspot and quantified future flood hazards under both upstream hydrological changes and downstream sea level rise. The low-lying Mekong Delta has long been identified as one of the world's most vulnerable river deltas to climate change and sea level rise (Adger, 1999; Ericson et al. 2006), however future impacts including extreme floods remains poorly quantified. In this study, we developed a model chain by linking a multi-site weather generator, the VMod hydrological model, and the Mekong Delta flood model to simulate extreme floods. Such modelling approach allowed to simulate and analyse changes in the frequencies and magnitudes of extreme floods under 'high-end' climate change (i.e. RCP8.5) and sea level rise scenarios.

Finally, a multidisciplinary study was implemented to develop measures and strategies to adapt to future hydrological changes, focusing on extreme floods in the Mekong Delta. Increasing flood risks represent a critical challenge for securing water-related safety and socioeconomic developments in the Mekong Delta. However, the question of how to effectively adapt to future floods remain largely unaddressed (MDP, 2013; Bastakoti et al. 2014). To develop adaptation measures and strategies to future floods, relevant data were collected from a systematic literature review and expert surveys. These data were then then analysed using novel analyses involving both qualitative (i.e. content analysis) and quantitative methods (i.e. statistical inference).

The following sections subsequently present the study's main results (Section 6.2); synthesis of the main findings (Section 6.3); methodological strengths and limitations (Section 6.4); scientific contributions (Section 6.5); recommendations for water management and climate change adaptation (Section 6.6) and finally, perspectives for future research (Section 6.7).

6.2. Main results

This section presents the study's main results for each research question. A summary of this study's main results in relation to research questions Q1-Q4 (Chapter 1) is provided in Table 6.1. The results for Question 1 showed that climate change will largely intensify the Mekong's hydrological cycle with overall increases in both annual and seasonal flows. Furthermore, both extreme high and low flows were projected to increase substantially, suggesting positive impacts on dry season water availability and higher flood risks during the wet season. The results for Question 2 demonstrated the river flows' high degree of susceptibility to future climate change, irrigation expansions and hydropower developments. Flow projections under the combined impacts of these driving factors showed substantial changes in the seasonal flow distribution as well as the complex mechanisms of future flow changes. The flood simulation results for Question 3 showed substantial increases in flood magnitudes and frequencies in the Mekong Delta caused by increasing upstream inflows and downstream sea level rise. While higher upstream inflow mostly affects the upper Mekong Delta, sea level rise increases flood hazards in the middle and coastal regions. Lastly, the study under the Question 4 resulted in a diverse set of measures and concrete strategies for adaptation to future floods. These measures and strategies demonstrated ample opportunities for the Mekong Delta to effectively manage future flood risks. In essence, effective adaptation requires innovative flood management approaches combined with improved governance and institutional capacities. All in all, this study projects substantial hydrological changes in the Mekong basin and at the same time shows potential adaptation to the future changes.

6.3. Synthesis

Hydrological changes are the major feature of the Mekong River's future flow regime (Research Objective 1)

All individual analyses in Chapters 2, 3 and 4 yielded robust signals of substantial changes in the Mekong's future flow regime. Future flow changes were consistently found across multiple modelling assessments (i.e. climate change impact modelling in Chapters 2 and 4; and integrated multiple drivers modelling in Chapter 3) and multiple scenarios of climate change, hydropower developments and irrigation expansions. Future flow regime changes are characterised by (1) altered temporal dynamics (i.e. annual, seasonal and monthly flows) and (2) changes in hydrological extremes (i.e. high flows, low flows and flood hazards). Regarding the flow's temporal dynamics, results from Chapter 2 and Chapter 3 showed that flow changes along the main rivers are, to a large extent, driven by largescale future hydropower developments. Increasing hydrological extremes are, on the other hand, primarily driven by climate change. At the basin scale, climate change will result in higher magnitudes and frequencies of high flows during the wet season and higher river flows during the dry season (Chapter 2). Chapter 4 further showed that upstream hydrological changes combined with sea level rise will increase flood hazards throughout the downstream Mekong Delta. Substantial increases in both frequencies and magnitudes of extreme floods highlight the Mekong Delta as a critical vulnerable region to future hydrological changes.

In addition to the consistent signal of future hydrological changes, the analyses in Chapters 2 and 3 also characterized the complex mechanisms of how the Mekong's hydrological regime responses to climatic and anthropogenic driving factors. Results from Chapter 3 further showed that future flow changes are driven by the cumulative impacts of climate change, irrigation expansions and hydropower developments. Contrasting directions of flow changes and different impact magnitudes under each considered driver result in both impact compensation and exacerbation, where the drivers offset and intensify each other's impacts on river flows, respectively. Similarly, the flood simulation results for the Mekong Delta (Chapter 2) also showed intensified flood hazards due to the accumulated impacts of sea level rise and upstream hydrological changes. All in all, the demonstrated complex mechanisms of future hydrological changes highlight the relevance of integrated modelling tools and approaches that allow for proper considerations of multiple driving factors and their interactions.

Future hydrological changes can be managed through multiple strategies and measures (Research objective 2)

Both the above discussed changing flow dynamics and hydrological extremes will likely have important consequences for water-related safety and for water resource uses and allocation. Without adequate and timely responses, future flow regime changes can affect economic growth; increase safety risks; affect local livelihoods and damage ecosystems. Increasing flood magnitudes and frequencies in the downstream Mekong Delta were identified in this study as one of the most critical risks, which require substantial, often transformative improvements in flood protection and flood resilience developments.

Despite the great challenges emerging from the future hydrological changes, results from several chapters in this study (especially Chapters 3 and 5) demonstrated multiple opportunities and measures to effectively manage future hydrological changes and to adapt to the associated risks. First, results from Chapter 3 showed that large parts of the hydrological changes are driven by future human activities (i.e. hydropower developments and irrigation expansions). This suggests that these changes are, to some extent, manageable through adjusting future developments. Undesirable hydrological changes could be avoided by limiting excessive, large-scale hydropower developments and irrigation expansions (Grumbinne and Xu, 2011; Ziv et al. 2012).

Table 6.1 Summary of the study's main results

Research questions	Main results
Q1: *What are the impacts of future climate change on the Mekong's flow regime and hydrological extremes?* (Chapter 2)	▪ Climate change will intensify the Mekong's hydrological cycle, resulting in substantial increases in seasonal and annual flows (between +5% and +16%, annually) in all mainstream stations. However, monthly river flows during the early wet season (i.e. June - July) show slight reductions of up to -7%. ▪ Extremely high flows during the wet season will increase in both magnitudes and frequencies, requiring further quantifications of future flood hazards and associated risks. Water availability during the dry season may increase due to overall higher river flows. ▪ Climate change impact signals derived from the CMIP5 projections are more robust than those reported in earlier studies, which were based on the CMIP3 projections. The uncertainty range of projected hydrological impact signals reduces substantially and cross-scenario agreements on directional changes improved markedly compared to earlier studies.
Q2: *How will the Mekong's flow regime change under the combined impacts of multiple driving factors including climate change, irrigated land expansion and hydropower developments?* (Chapter 3)	▪ The Mekong's flow regime is highly susceptible to future climate change, hydropower developments and irrigated land expansions. Hydropower developments strongly alter the wet-dry season flow distribution; climate change results in annual flow increases (up to +16%) and irrigation expansions consistently reduce river flows (up to -3%, annually). ▪ The flow regime shows substantial changes under the combined impacts of the three driving factors, characterized by (1) consistent dry season flow increases, up to +150% and (2) contrasting flow reductions (up to -25% for June - October) and flow increases (up to +36% for November - December). Flow changes are driven by both impact compensation (e.g. climate change induced flow increases are compensated by dams operation during the late wet season) and impact exacerbation (e.g. accumulated flow reductions caused by all drivers during the early wet season) ▪ Substantial flow changes likely result in important consequences for crop production, flood risks, ecosystem dynamics and local livelihoods. Direct consequences for water resources include

	higher dry season water availability and higher risks of water shortage during the early wet season.
Q3: *How will upstream climate change induced-hydrological changes and downstream sea level rise affect flood hazards in the Mekong Delta?* (Chapter 4)	▪ Flood hazards will increase substantially throughout the whole Mekong Delta, due to higher upstream inflows and sea level rise. Both the flood frequencies and magnitudes (i.e. flood depths) will increase, with flood depth increases of up to +0.9 m under the future 500-year flood events. ▪ Upstream hydrological changes and downstream sea level rise show distinct spatial impact distributions: Flood hazards in the upper delta will be mainly affected by higher upstream inflows, while the middle and coastal delta will experience increased flood hazards caused primarily by sea level rise. ▪ Increasing flood hazards under climate change poses critical safety risks for inhabitants and infrastructures, thus requiring better flood protection and more flood resilient developments.
Q4: *What are the suitable measures and strategies for the Mekong Delta to adapt to future flood risks?* (Chapter 5)	▪ A total of 19 challenges for managing future floods were identified. The challenges exhibit high degrees of diversity, context specificity and different important levels. These features imply that effective adaptation measures need to cover multiple aspects of flood management and tailored to the local contexts. ▪ Main strategies for adapting to future flood risks include (S1) Create a more enabling environment for flood management; (S2) Strengthen and diversify the flood management portfolio; (S3) Foster cross-boundary interactions; (S4) Improve capacity and resources; (S5) Improve data and decision support; and (S6) Innovate and shift flood management approaches. ▪ Effective adaptation to future flood requires looking beyond the conventional management approach, which focuses strongly on technical fixes. Instead, integrating multiple innovative measures, combined with suitable governance and institutional settings offer great opportunities to minimize flood risks under climate change and accelerating socioeconomic developments.

Second, results from Chapters 3 and Chapter 5 also demonstrated multiple opportunities and concrete measures to actively manage future hydrological changes. At the basin-scale, the impact compensation effect where individual driving factors partly offset each other's impacts suggested the possibilities to actively manage the Mekong's flow regime using infrastructural measures. For example, hydropower dam operations could be adapted to allow for active flood control or irrigation water storage during dry periods. Largescale hydropower development with new dam constructions, however, should be limited given the resulting substantial hydrological impacts as demonstrated in Chapter 3. Future developments in the Mekong region including food and energy production require careful considerations of their costs, benefits and how these costs and benefits are distributed across different regions, actor groups and economic sectors.

The regional analysis for the downstream Mekong Delta (Chapter 5) provided a relatively large and diverse set of measures to effectively adapt to the increasing flood hazards. The results show that optimizing the existing flood prevention infrastructures (i.e. dikes, gates and flood release canals) and developing innovative technical measures (e.g. create room for the river) can help to cope with more extreme floods. Furthermore, the identified adaptation measures and strategies show vast potentials of improving the institutional and governance capacities for flood risk management. Of special importance in this regard is to improve coordination in flood management, foster communication and information exchanges between different regions and actor groups. All in all, analyses at both the basin-wide and Mekong delta levels stress the importance of (1) coordination across regions, actor groups and economic sectors and (2) innovations looking beyond the conventional, business as usual management approach.

6.4. Reflections on strengths and limitations of the study's methodology

While previous chapters (i.e. Chapters 2 to 5) dedicate sufficient discussions on the individual tools and approaches, this section provides a critical reflection on the overarching research framework applied in this thesis. The reflection focuses on the strengths and limitations of the study's main methodologies, focusing on the scenario-based modelling assessments, and the combined quantitative-qualitative approach for adaptation appraisal.

The scenario-based modelling exercises for hydrological impact assessment

The developed modelling framework in this study served the main purpose of conducting an integrated hydrological impact assessment, covering both basin-wise and regional (i.e. Mekong Delta) hydrological processes. By coupling a newly developed crop and irrigation water module, and a hydropower dam operation module into the VMod hydrological model, the modelling framework allowed to quantify the impacts of main driving factors on the Mekong's flow regime. This study considered the most important factors that will likely affect river flows, namely climate change, irrigation expansions and hydropower developments. Furthermore, the coupled VMod - Mekong Delta flood models represent an operational modelling framework to assess future flood hazards in the downstream river delta taking into account changes in both upstream hydrology and downstream sea level rise.

The developed modelling framework complements and furthermore overcomes several important limitations of analysing observed data as an alternative approach to study hydrological changes. Although statistical inferences applied on observed data (i.e. flows and water levels) proved useful in analysing past dynamics (see, for example Delgado et al. 2010; Dang et al. 2016) and in projecting short-term future dynamics (Dung et al. 2013), this approach exhibits important limitations in handling non-stationarity and future uncertainties. Chapters 2, 3 and 4 showed that both nonstationary and future uncertainties are highly relevant for the Mekong basin, where the flow regime is increasingly perturbed by climate change and emerging anthropogenic factors such as irrigation expansions and hydropower developments (MRC, 2011; Delgado et al. 2012). Under such context, future flow characteristics can differ largely from the observed patterns, thus emphasizing the limited capability of analysing observed flow data for future projections (Delgado et al. 2012). When combined with multiple scenarios of future climate change, irrigation and hydropower developments, the modelling approach allowed to capture the possible range of future hydrological changes following the future dynamics of the driving factors. To conclude, the scenario-based modelling approach allowed looking into the future of the Mekong's flow regime and capturing changes that potentially go beyond what have been observed in the past. At the application end, projected future flow changes based on modelling assessments provide meaningful references, especially in terms of future extreme floods for decision making and water resources planning.

Hydrological impact assessments using scenario-based modelling, however, also exhibit important limitations worth discussing. The ultimate purpose of all modelling assessments in this study is to quantitatively link the dynamics of the driving factors to hydrological dynamics (i.e. river flow and water level dynamics) and but inherent uncertainties of different types emerge in each of the assessments. An overview of the types of uncertainties that relate to projecting future hydrological changes in this study is provided in Table 6.2. In summary, uncertainties in the hydrological impact assessments mostly relate to (1) model parameterisations and (2) future dynamics of the driving factors of flow regime changes. Uncertainties in the model parameterisations can result in imperfect model simulation performance, where the simulated flow dynamics partly departs from those of observed data. This uncertainty applies to both the VMod model (shown by imperfect reproduction of the historic flow regime, high flows and low flows), and the

Mekong Delta flood model (shown by imperfect reproduction of the floodwater levels and flood extents). This study paid special attention to model parameterisations and calibrations to ensure adequate treatment of the relating uncertainties. In particular, the VMod model was thoroughly calibrated and validated using observed daily data for a 20-year period and for multiple locations (i.e. seven mainstream stations). The calibration and validation results showed reliable model performance for multiple aspects of the flow dynamics, including flow regime, high flows and low flows. Similarly, the Mekong Delta flood model was selected amongst other potential models based on its demonstrably reliable model performance, shown by relatively good reproduction of both floodwater level and inundation extents (Dung et al. 2010). Finally, the VMod and the Mekong Delta flood model in this study were developed and calibrated separately by two different research groups during different time periods (Lauri et al. 2006; Dung et al. 2011). These separated model developments and calibrations could potentially affect the overall reliability of the combined modelling framework. The modelling framework's performance, however, is justified by demonstrated good skills of the individual models. Ideally, seamless linkages of modelling tools through joint model development and calibrations could help to improve the overall simulation performance.

Regarding the uncertainties relating to future dynamics of the driving factors of future hydrological changes, it is important to stress the grand challenge of projecting future changes in the monsoonal climate system (Delgado et al. 2012), irrigation expansions and hydropower developments (MRC, 2011). Although projecting the future dynamics of these driving factors are not the main focus of this study, uncertainties of such projections can affect the robustness of the derived hydrological impact signals. To address this type of uncertainty, this study, wherever possible, derived hydrological impact signals based on multiple scenarios of the driving factors. Such scenario-based impact assessments allowed to capture the range of possible future hydrological changes, thereby reflecting future uncertainty into the projected impact signals. This study, however, did not explicitly account for the possible interactions between the drivers, and the feedbacks from hydrological changes to their future dynamics. For example, because of higher flood risks under future climate and increasing irrigation water demand due to irrigation expansions, hydropower dam operations could be adapted to serve multiple objectives of energy production, dry season water storage, and flood mitigation (Giuliani et al. 2016). Ultimately, changing hydropower dam operation will impact river flows and might require proper quantification depending on the impact magnitude. To conclude, future dynamics of the Mekong River flow's main driving factors could potentially change due to their interactions and feedbacks from hydrological changes. Such interactions and the resulted impacts on the future flow regime therefore constitute a relevant research question for future studies.

Table 6.2 Overview of the types of uncertainties in projecting future hydrological changes and treatments in the study

Type of uncertainties	Main aspects of uncertainties relevant for this study	This study's treatments of uncertainties
Uncertainty in model parameterizations	Climate models cannot perfectly reproduce historic climate conditions. Historic and future climate projections therefore entail uncertainties caused by the climate models' parameterizations.	Downscaling and bias correcting climate data based on observed or reanalysis historic climate data.
	The VMod hydrological model cannot perfectly reproduce the Mekong's historic flow regime; high flows; and low flows. Simulated river flows therefore entail uncertainty caused by VMod's imperfect parameterization.	Thorough calibration and validation for VMod model over long time periods (1981-2001). Simulation results are analysed and reported for locations where the model performance is demonstrably reliable based on validation against observed daily flow data.
	The Mekong Delta flood model cannot perfectly reproduce the water levels and inundation extents during flood events. Simulated water levels and flood extents therefore entails uncertainty caused by the flood model's imperfect parameterization.	The flood simulation model was selected based on its demonstrated good performance for reproducing both floodwater levels and flood extents.
Uncertainty in future dynamics of the driving factors	Scenarios of future climate change, irrigation expansions and hydropower developments all entail uncertainties about how these drivers will change over time. These uncertainties about the drivers' future dynamics are transferred into uncertainties about the future hydrological changes.	Using multiple scenarios for the future dynamics of the driving factors wherever possible (climate change and irrigation expansions). This approach allows for capturing a possible range of future hydrological changes.
	The future dynamics of the drivers were projected without explicit considerations of the interactions between factors, and of the potential feedbacks from hydrological changes to the factors. Such missing interactions constitute one source of uncertainty in projecting future driver dynamics and will ultimately transfer to the hydrological impact uncertainty.	No explicit uncertainty treatment applied because we assumed smaller hydrological impacts of the driver interactions compared to their direct impacts.

The combined quantitative-qualitative analysis for adaptation appraisal

To develop effective measures and strategies for adaptation to future hydrological changes (i.e. Objective 2), this study developed and implemented multidisciplinary research approaches where quantitative methods (i.e. modelling and statistical inferences) were combined with qualitative methods (i.e. expert survey and content analysis). These multidisciplinary approaches were applied in both an individual chapter (Chapter 5) and across chapters (linking Chapters 2, 4 and 5). At the cross-chapter level, combinations of model results with expert survey and content analysis helped to target adaptation to the key aspects of future hydrological changes (i.e. impact focus) and to the most vulnerable regions (i.e. regional focus). Figure 6.1 illustrates the added values of hydrological modelling for shaping adaptation's focuses, where the model results identified increasing flood risks as a focal impact, and highlighted the Mekong Delta as a critical vulnerable region. Furthermore, the model results also showed substantial hydrological changes with potentially serious consequences (especially increasing future floods). This created strong rationales for the follow-up appraisal of adaptation measure and strategies.

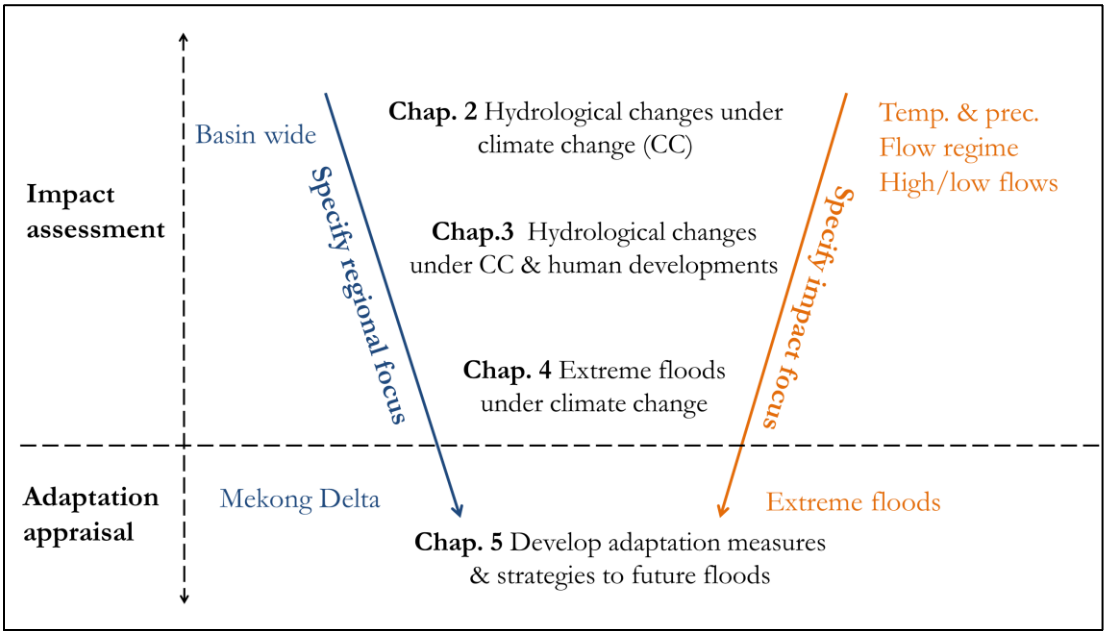

Figure 6.1 Use of hydrological impact assessment results for shaping adaptation focuses. Modelling assessments specified the Mekong Delta as a key vulnerable hotspot (regional focus) and increasing extreme floods as the key impact focus.

In addition to creating the necessary focuses for adaptation, the combined qualitative-quantitative approach also showed important benefits for designing and implementing adaptation measures and strategies. While expert surveys and content analysis provided potential adaptation interventions, statistical analyses of the experts' recommendation frequencies (i.e. how often an intervention is recommended) helped to further tailor them to specific challenges in adaptation to future floods. As such, the study provided insights about how to address different aspects of flood management using different sets of adaptation measures and strategies. All in all, the combined quantitative-qualitative analyses allowed to properly specify key impacts of future hydrological changes, key vulnerable regions and configurations of multiple adaptation interventions dedicated to specific aspects of flood management.

In essence, hydrological impact modelling followed by adaptation appraisal represents an anticipatory approach to manage future hydrological changes. Ad-hoc responses to hydrological changes, on the other hand, represent an alternative approach which can be more efficient in the short term due to generally lower capacity and resource requirements. However, adaptation to future hydrological changes following an anticipatory approach is more effective in the longer term (Fankhauser et al. 1999). First, anticipatory adaptation is less prone to surprises such as extreme floods surpassing historic records or flooding in currently safe areas along the Mekong Delta's coast due to sea level rise as shown in Chapter 4. Second, anticipatory adaptation allows for long-term, large investments because this often requires joint adaptation and accumulation of the necessary resources over a long time period (Mendelsohn, 2000). This notion is especially relevant for the Mekong region, where capacities and resources are rather limited.

6.5. Scientific contributions to understanding and managing hydrological changes

Adequate understandings and effective management of future hydrological changes in large rivers including the Mekong represent important, yet highly challenging research topics (Oki and Kanae, 2006; Wagener et al. 2010; Johnston and Smakhtin, 2014). This is because addressing such changes requires knowledge, tools and approaches that often stand at the forefronts of several scientific disciplines including hydrology, water management and climate change impact and adaptation assessments. Another challenging aspect of such topics is that their combined quantitative-qualitative nature requires to develop research frameworks that can integrate and thus effectively utilize multiple scientific disciplines. This multidisciplinary research contributes to the above discussed challenges through (1) advancing knowledge and understandings about projecting and managing hydrological change and related risks; and (2) demonstrating several scientific approaches, tools and relevant datasets for other related studies.

While many previous studies quantified climate change impacts on river flows focusing on annual, seasonal and monthly timescales, impacts on hydrological extremes remain a largely unaddressed knowledge gap for the Mekong (Campbell, 2007; Kiem et al. 2008). This is the first study to explicitly quantify future changes for hydrological extremes, including both high flows and low flows. Additionally, the robust hydrological impact signals derived from a relatively large climate change scenario ensemble (five GCMs and two RCPs) represent an important contribution to the current scientific body of the Mekong's future flows under climate change. Contrary to prevalent uncertainties reported in earlier studies, projected future flows in this study show strong cross-scenario agreement on change's directions and substantial reduction in the uncertainty range. More robust hydrological impact signals found in this study not only further solidify the current knowledge body about hydrological responses to climatic stimuli, but also open up new research directions focusing on secondary impacts, for example on aquatic ecosystems, flood damages or food and energy production. The modelling framework presented in Chapter 4 demonstrates an useful approach to further link extreme high flows to flood hazards in the downstream Mekong Delta. This modelling approach resulted in unique results of spatially explicit, probabilistic (up to 500-year return period) estimates of future flood hazards. The results on flood estimates provide the much needed, yet largely unavailable future projections for long-term water management and climate change adaptation planning, especially in terms of managing extreme floods in the Mekong Delta.

This study took an integrated approach to assess future hydrological changes and subsequently to develop adaptation measures and strategies to floods. Such research approach is illustrated through the integrated hydrological impact assessment (Chapter 3), and the integrated modelling combined with qualitative adaptation appraisal (Chapters 2, 4, and 5 combined). While other recent studies have started quantifying the combined impacts of multiple driving factors on the Mekong's flows, this study offers one of the most comprehensive assessments of such type owing to the diversity of driving factors and the large set of future scenarios included in the analysis. Together with several other studies (e.g. Lauri et al. 2012; Piman et al. 2013), the integrated hydrological impact assessment in this study contributes to better understandings about the complex mechanisms of the Mekong's future hydrological changes under climate change and human developments.

This study focuses on quantifying and adapting to future flow regime changes in the Mekong river basin and delta. However, the research approaches and yielded results can also be relevant for other studies. Regarding scientific approach, the developed model chain comprising of a basin-wide hydrological model and a delta flood simulation model could be applied to similar type of river basins to study flow dynamics, quantify flood hazards or assess impacts of climate change, land use change or dam operations. The fact that this study used several global and continental input datasets implies relatively straightforward replication of the modelling approach to other river basins. These datasets include the downscaled and bias corrected CMIP5 climate projections (Taylor et al. 2012), the WATCH Forcing Data (Weedon et al. 2011) and the APHRODITE precipitation data (Yatagai et al. 2012). Similarly, the adaptation appraisal based on expert survey and content analysis is widely applicable for different geographic regions and research topics.

Several datasets developed in this study could be relevant for other studies on different topics. The downscaled and bias corrected climate change data for five GCMs and two RCPs could well be used in other climate change impact assessments, such as impacts on crop production, forest and aquatic ecosystems. The simulated daily flow data for mainstream stations along the Mekong can serve as boundary condition for further assessing the impacts of hydrological changes, or for testing effectiveness of proposed management measures. For instance, daily flow data at Kratie station (i.e. inlet of the Mekong Delta) could be used as the upstream boundary condition to test the effectiveness of several flood management options in the delta, including dike constructions, natural floodplains restorations or constructing emergency flood release canals. Studies on flood risks in the Mekong Delta, especially those focusing on the low-frequency and high-damage events, can benefit from this study through using the probabilistic flood hazard estimates. Last but not least, the identified measures and strategies to adapt to future flood risks can be used as starting points for more detailed cost-benefit and feasibility analyses.

6.6. Recommendations for water management and climate change adaptation

This research addresses the needs for improved quantifications of future hydrological changes, and for effective adaptation to the associated risks. Our results showed that climate change and accelerating socioeconomic developments (i.e. irrigation and hydropower developments) will largely alter the Mekong's flow regime and thereby introducing important challenges for securing water-related safety and sustainable water uses and allocations. Furthermore, this study also highlights ample opportunities for more sustainable basin-wide water management, and for adaptation to future floods as one of the most important future risks in the populous, yet highly vulnerable Mekong Delta. Based on the main findings, several recommendations for water management and climate change adaptation are formulated below.

Adaptation to future hydrological changes is strongly desirable

Adaptation to future hydrological changes, especially to the increasing flood risks and altered flow distribution between the wet and dry seasons, are crucial for the people, economic sectors and natural ecosystems in the Mekong basin. This study projected substantial increases in flood hazards throughout the Mekong Delta under future upstream hydrological changes and sea level rise and demonstrated critical vulnerabilities including higher flood risks. Overlaying population density and future flood hazard maps shows that densely populated areas, especially those located in the middle and coastal delta zones are amongst the most severely affected areas throughout the whole delta (Figure 6.2). Timely and adequate adaptation to future floods is therefore crucial to secure safety of millions of people, infrastructures and various economic activities.

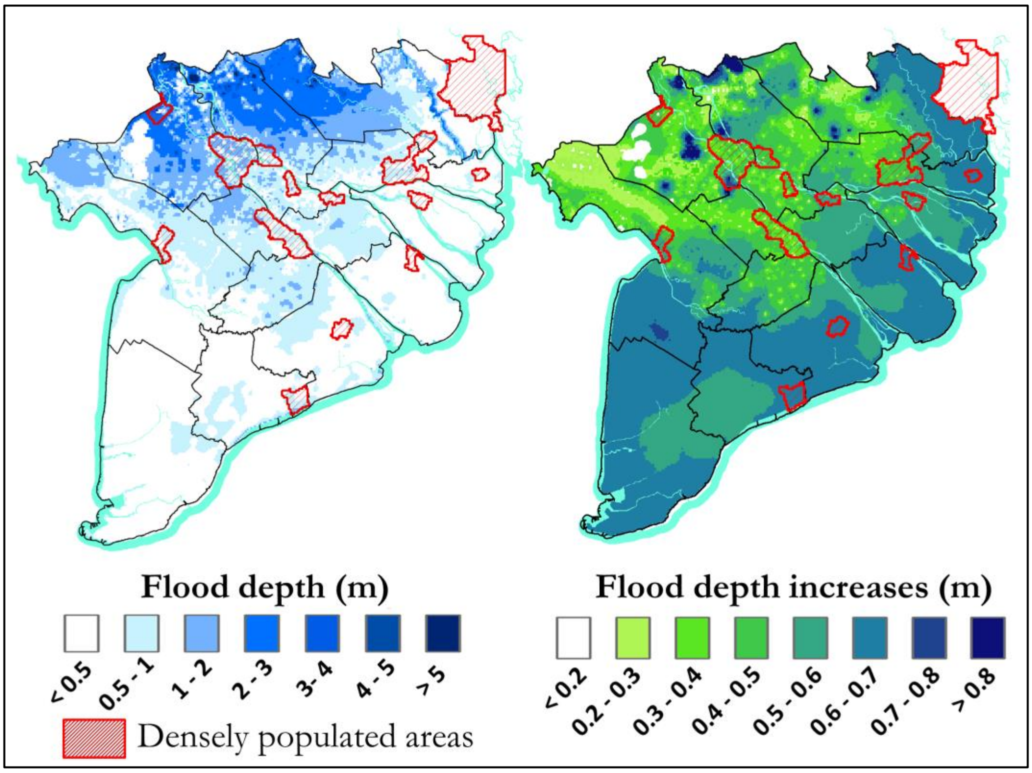

Figure 6.2 Future extreme floods increase safety risks for densely populated areas in the Mekong Delta. Maps present maximum flood depths under very extreme floods (i.e. 500-year return period; left panel) and projected flood depth increases caused by upstream hydrological changes and sea level rise by the 2050s (right panel). Population density data for 2015 were derived from the QPWv4 dataset (GPWv4, 2016), where densely populated areas with population density over 1000 people/km^2 were highlighted.

Additionally, uncertainties about future hydrological changes should no longer hinder investments in adaptation, especially in the vulnerability hotspots. Some degrees of uncertainty surrounding the Mekong's future flows will likely remain, despite rapid scientific advancements and growing empirical data. However, multiple robust signals of future hydrological changes from this study and other recent studies (Lauri et al. 2012; Smajgl et al. 2015) provide strong rationales and incentives for timely and adequate adaptive interventions. In this context, adaptation should focus on no-regret and flexible measures, which allow for justifying present investments and adjusting the measures as the future unfolds. In the specific case of the Mekong Delta, improving institutional and governance capacities to better facilitate technological innovations and alternative flood management approaches are typical examples of such non-regret investments.

Sustainable water resources uses and allocation require better coordination of future developments and water management

Results from this study demonstrated that uncoordinated future development activities including hydropower dam construction and irrigation expansion can have potentially serious consequences for agriculture, water supplies and ecosystems in the Mekong basin. Similarly, analysing current flood management in the Mekong Delta also showed that lack of coordination results in poor performance of existing flood management interventions, as shown by the relocated flood risk across the delta rather than reduced floods. We therefore recommend to improve coordination across regions, countries and economic sectors for more effective and sustainable water resources management. In this regard, strengthening international, cross-sectoral dialogues and negotiations is of special importance. This can be done through strengthening the roles of existing international bodies such as the Mekong River Commission and the Association of Southeast Asian Nations – ASEAN. Additionally, new dialogue channels and mechanisms should also be explored through, for example, bilateral collaborations or economic forums (e.g. the 2016 World Economic Forum on the Mekong region). Finally, spatial and sectoral coordination for sustainable water uses and allocations should be supported with a more effective environmental monitoring scheme combined with environmental impact assessments. Data and insights from monitoring and impact assessments will form a strong basis for such improved international and cross-sectoral coordination.

Technological innovations and alternative water management approaches offer ample opportunities for managing and adapting to hydrological changes

In essence, technological innovations refer to developing new, more sustainable measures for water allocations (temporal, spatial and cross-sectoral) and for water-related risks management. Several directions for innovation were illustrated and discussed throughout this study, including optimizing water allocations and mitigating extreme floods. Sensible reservoir operation or adapting agricultural production (e.g. using new crops or adjusting crop and irrigation calendars) can effectively redistribute river flows over time, which represent potential measures to avoid critical low flow periods and saltwater intrusion in the downstream Mekong Delta. The same principle applies to extreme high flow management, where operations of existing hydropower dams could be adjusted to allow for sufficient floodwater storage capacity. The question of constructing new hydropower dams, however, remains open and should be subjected to careful environmental and socioeconomic impact assessments to avoid undesirable externalities and increased risks. In order to allow technological innovations to emerge and eventually taken up at sufficiently large extents, providing suitable conditions from within the water management regime is crucial. Focusing on technological innovations and the institutional and governance capacities to improve adaptive capacity to future hydrological changes are especially important in this respect.

6.7. Outlook and recommendations for future research

This multidisciplinary research contributes to the current knowledge body of future hydrological changes and adaptation in large river basins experiencing climate change and rapid socioeconomic developments (Keskinen et al. 2010; Varis et al. 2012; Bastakoti et al. 2014). The modelling results provided a comprehensive and detailed quantification of future changes in the Mekong's flow regime and hydrological extremes including extreme floods in the downstream delta. The follow up adaptation appraisal provided concrete measures and strategic directions to adapt to the increasing future floods. To further advance this important knowledge body, several research directions and research questions are recommended.

While this study focused on climate change, irrigation expansions and hydropower developments as the main drivers of future hydrological changes, there are potentials for further research based on the developed modelling framework for integrated hydrological impact assessment. Future studies, which broaden the scope of analysis by including more drivers (e.g. domestic and industrial water uses), could yield more comprehensive and realistic projections of future hydrological changes. Additionally, explicitly accounting for driver interactions and feedbacks between hydrological changes and the drivers will be useful to better characterize the Mekong's complex hydrological regime, ultimately yielding more robust projections. This study projects increases of up to 1.8 million hectares of irrigated land within the coming three decades and shows substantial impacts on river flow reductions. While Haddeland et al. (2006) demonstrate considerable irrigation impacts on increasing evapotranspiration and decreasing surface temperature, it might be relevant for future studies to account for the impacts of irrigation expansions on local climate conditions and how these factors together affect river flows. Similarly, changing hydropower dam operations and the resulting hydrological impacts should be considered, given the substantial future changes in the flow regime under climate change and irrigation expansion projected in this study.

Another interesting angle to look at the drivers' interactions is to analyse cross-sectoral and upstream-downstream optimisations for sustainable water uses and river flow management. Findings from this study and other studies (e.g. Ziv et al. 2012 and Piman et al. 2013) show strong interlinkages between water resources, food and energy production in the Mekong basin. Optimisation studies are therefore highly relevant to address issues of cross-sectoral competitions and unsustainable upstream-downstream water allocations. In this regard, the water-food-energy nexus (Hoff, 2011) represent a promising approach to analyse potential trade-offs and synergies relating to basin-wide water uses and allocations. Given the great economic and ecological values of the aquatic ecosystems in the downstream Mekong region, including ecosystems to the nexus analyses should also be considered (Ziv et al. 2012; Arias et al. 2014). Analysing the hydropower-food nexus using modelling approach was demonstrated feasible for the Mekong (Pittock et al. 2016) and such approach should be further developed to include water and ecosystem elements. To conclude, an operational basin-wide optimisation scheme with adequate treatments of the key synergies and trade-offs between main sectors and regions would constitute an important breakthrough, both in terms of practical implementation of the nexus approach, and of decision support for the Mekong basin.

Motivated by the long-term and potentially serious consequences of future hydrological changes, this study focused primarily on long-term changes that are representative at timescales ranging from one decade up to 30 years. However, analysing hydrological changes at shorter timescales is useful to consider specific events or critical time periods that can have short-term, yet substantial consequences. We therefore recommend future modelling studies to focus on river flow analyses during specific dry and wet periods. In this regard, studies should pay special attention to the El Niño and La Niña periods under climate change, given their strong influences on flow dynamics (Räsänen and Kummu, 2013). Additionally, while the hydropower dam's impacts under routine operations were established in this study, irregular operations (e.g. changing operational rules during critical dry/wet years, or reservoirs filling up after construction) can have large impacts on river flows, therefore calling for stronger attention in future studies. Similarly, future flood studies can include storm surges, which exert extremely high water levels along the coast, to better account for the worst-case flood scenarios for the low-lying Mekong Delta. To conclude, all the above discussed new research directions can further improve the current understandings about the Mekong's hydrological regime with regard to event-specific behaviours.

Next to the challenges relating to future hydrological changes, this study also highlighted the potential opportunities that come along with these changes. Future opportunities generally focus on sustainable flow regime management through optimising future developments; and on transforming the current water management approach to allow for timely and effective adaptive interventions. In this context, how to practically realize these opportunities constitute an important research topic. Future studies should therefore focus on developing economic and policy instruments to encourage dialogues and negotiations between sectors, regions and countries, ultimately resulting in collaborations for sustainable water management. Another important research question relating to realizing future opportunities is to identify tipping points (Kwadijk et al. 2010) and to develop adaptation pathways (Haasnoot et al. 2012), especially in vulnerable hotspots including the Mekong Delta. Studies on tipping points and adaptation pathways can provide concrete and long-term guidance to organize and coordinate individual adaptation investments that collectively allow for transformative, large-scale adaptation. All in all, the research framework and insights from this study contribute to create new research opportunities relating to sustainable water uses and allocations.

Future hydrological changes and associated risks under climate change and accelerating socioeconomic developments represent one of the most important challenges for the Mekong region during the 21st century. Proper quantifications of these future changes and implementing effective responses are therefore extremely important to ensure a safe Mekong River with undisrupted and fair provisions of critical services and values for the region's economies, its people and its unique natural ecosystems.

Supplementary information A

Calculating discharge biases (RB) and Nash Sutcliffe Efficiency (NSE) indices

Relative bias equation:

$$RB = \frac{Si}{Oi} \qquad (A1)$$

Where:

RB: Relative biases

Si: Simulated value of yearly river flow or Q5 or Q95 values

Oi: Observed value of yearly river flow or Q5 or Q95 values

Nash-Sutcliffe Efficiency equation:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Oi-Si)^2}{\sum_{i=1}^{n}(Oi-\bar{O})^2} \qquad (A2)$$

Where:

NSE: Nash-Sutcliffe efficiency index

Si: Simulated daily river discharge

Oi: Observed daily river discharge

Ō: Mean value of observed daily river discharge

Reference

Nash, J., Sutcliffe, J.V. (1970) River flow forecasting through conceptual models part I—A 18 discussion of principles. J Hydrol 10 (3):282-290

Supplementary information B

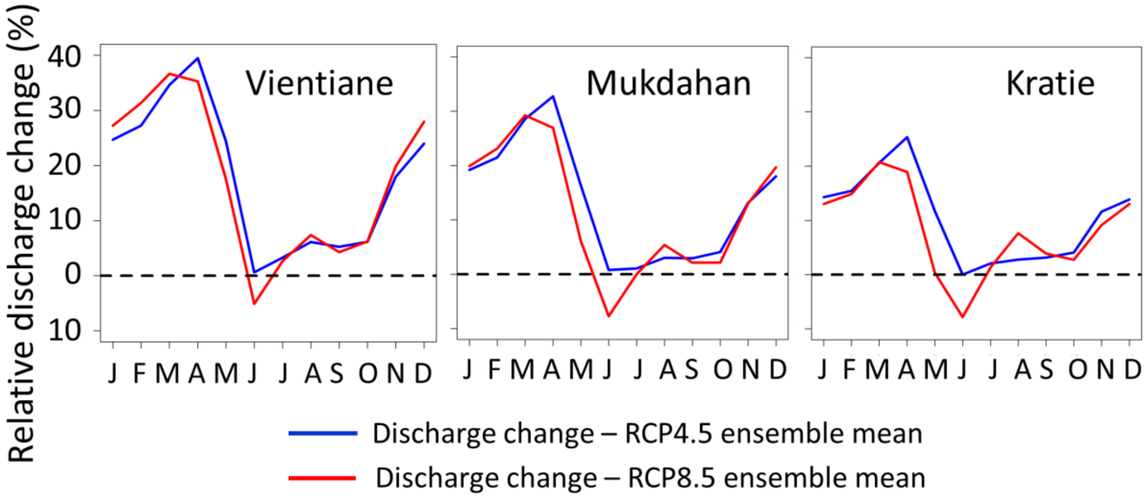

Figure B1 Relative monthly discharge change (%) at main stations under climate change

Supplementary information C

Technical descriptions of the hydropower dam operation module

The hydropower dam operation module was developed by Lauri et al. 2012, which estimates the optimal monthly outflow for each dam using a linear programing optimisation method. The main objective of the optimisation is to maximize the annual outflows through the hydropower turbines, thus achieving maximum annual hydropower production. The hydropower dam operations were optimized using a set of parameters, namely active storage, monthly inflow, minimum outflow and optimal outflow. The optimisation's parameters and objective functions are described as follows:

Parameters:

q_i: monthly outflow from reservoir
o_i: monthly overflow from reservoir
qin_i: estimated monthly inflow, i=1..12
s_i: reservoir active storage, i=1..12
$qmin_i$: minimum value for outflow, i=1..12
qopt: maximum flow through turbines
smax: reservoir active storage
k: parameter for storage water level
sign(x): function, returns -1 if x<0, else +1
ndi: days in month i, i=1..12

Objective (i=1..12):

$$\text{Max } \Sigma(q_i + k \text{ sign}(qopt - qin_i))$$

Constraints (i=1..12):

1) $s_i + s_{i+1} + nd_i (qin_i - q_i - o_i) = 0$;
2) $q_i > qmin_i$
3) $q_i < qopt$
4) $s_i < smax$
5) $q_m = q_n$; m,n = 1,2; 2,3; 3,4; 4,5

Optimal outflows from hydropower dams are estimated using linear programming (Dantzig and Thapa, 1997). Operation rules are developed sequentially from the most upstream dams down to the most downstream ones. This ensures that any dam's operation accounts for the influence of all upstream dams.

References

Dantzig, G. B. and Thapa, M. N.: Linear programming 1: Introduction, Springer-Verlag, 997.

Lauri H, de Moel H, Ward PJ, Räsänen TA, Keskinen M, Kummu M. 2012. Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge. Hydrol. Earth Syst. Sci., 16: 4603-4619. DOI: 10.5194/hess-16-4603-2012.

Supplementary information D

Technical descriptions of the crop and irrigation module

The crop and irrigation module in this study was developed based on the FAO AquaCrop model version 4.0 (FAO, 2012). Following the AquaCrop's approach, the module simulates crop growth following five steps:

Step 1 – simulation of the soil water balance

Step 2 – simulation of the green canopy development

Step 3 – simulation of crop transpiration

Step 4 – simulation of the above-ground biomass

Step 5 – partitioning of biomass into yield

The detailed simulation scheme adopted from AquaCrop is presented in Figure D1.

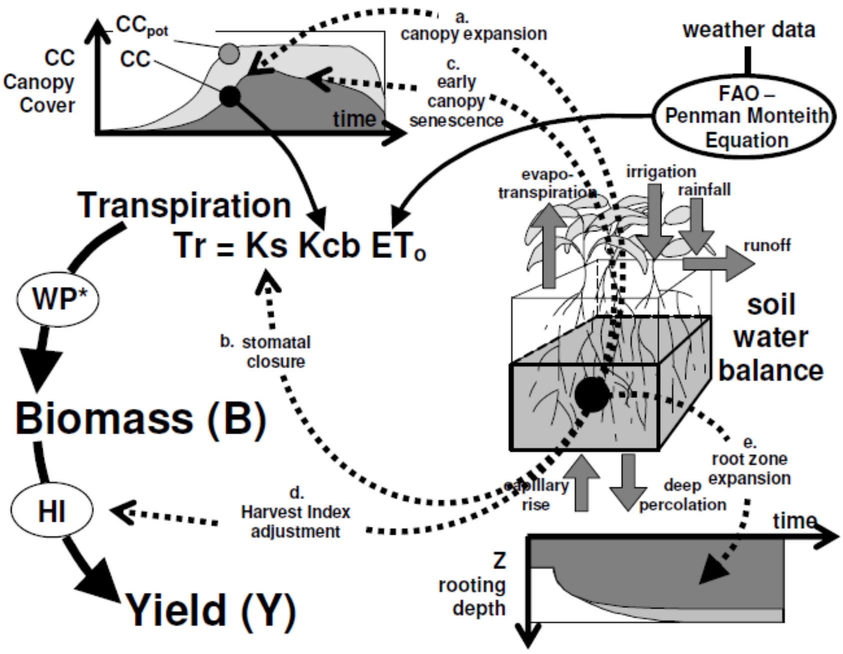

Figure D1 AquaCrop model's simulation scheme (FAO, 2012). With CC being the simulated canopy cover, CC_{pot} is the potential canopy cover; Ks is the water stress coefficient; Kcb is the crop coefficient; ETo is the reference evapotranspitation; WP* is the normalized crop water productivity; and HI is the Harvest Index.

Since this study focus on wet rice as the most dominant crop in the Mekong basin, a wet-rice-specific scheme was developed to calculate crop irrigation demand. The irrigation scheme calculates crop irrigation demand as sum of three components.

The first component accounts for the amount of water to saturate rice fields i.e., to bring soil water up to field capacity at the beginning of the cropping season. The amount of irrigation water needed to saturate rice field is calculated using the root zone depletion term (Dr), representing the difference in soil water contents between saturated and the actual soil condition.

$$Dr = W_{rFC} - W_r = 1000 * (\Theta_{FC} - \Theta) * Z$$

Where

Dr: Root zone depletion (mm)

W_{rFC}: soil water content of the root zone at field capacity (mm)

W_r: actual soil water content of the root zone (mm)

Θ_{FC}: Volumetric water content at field capacity (m^3/m^3)

Θ: Actual water content at the root zone (m^3/m^3)

Z: Effective rooting depth

The second component accounts for the amount of water to flood the fields i.e., rice ponding during the cropping period. The ponding water levels are maintained within a range of 75 to 150 mm, which was derived based on field observations. Water levels in the rice field are controlled by compensating for water losses caused crop evapotranspiration and, to a lesser extent, infiltration to deeper soil layers. The required water for maintaining the ponding water levels constitutes the third component of the gross irrigation demand. Evapotranspiration is calculated as sum of evaporation (Es) and crop transpiration (Tr) as follows:

$$Es = K_r * (1\text{-}CC) * K_{ex} * ETo$$

$$Tr = K_s * CC * K_{ctr,x} * ETo$$

Where

K_r: Evaporation reduction coefficient to adjust Es when soil water is insufficient to respond to atmosphere's evaporative demand.
CC: Crop canopy cover
K_{ex}: Maximum soil evaporation coefficient for fully wet, not shaded soil
ETo: Reference evapotranspiration rate from a grass surface.
Tr: Crop transpiration
K_s: Soil water stress coefficient to adjust Tr when soil water is insufficient to respond to atmosphere's evaporative demand.
$K_{ctr,x}$: Maximum crop transpiration coefficient

References

FAO, 2012. AquaCrop crop model reference manual - Chapter 3 Calculation procedure. Land and Water division, Rome, Italy.

Supplementary information E

Systematic literature review flood management challenges in the Mekong Delta is available online at https://www.dropbox.com/s/dw02wnytmxo11xp/Supplement_B.pdf?dl=0

Supplementary information F

Questionnaire survey: Flood management in the Vietnamese Mekong delta: Identify challenges and explore solutions

Note: The survey was implemented online using Lime Survey platform

Introduction

We welcome and thank you very much for taking your time to participate in our online-survey!

The objective of this survey is to draw on knowledge and experience of experts to gain better understanding about the challenges for flood risk management and explore possible solutions to address these challenges in the Vietnamese Mekong River Delta (hereafter the Mekong delta).

Throughout the survey, you will be asked to provide your expert judgements and recommendations on various aspects of flood management challenges. The questions are in multiple choice and open-ended formats. We would appreciate it very much if you provide detailed and specific answers to the open-ended questions. This would help us to draw meaningful conclusions from analysing the survey results. The survey takes approximately 15 minutes.

If you have any question(s), please contact our survey administrator, Mr. Long Phi Hoang at Long.hoang@wur.nl (+31 317 485 928).

Thank you in advance for your support in our research!

Research team:

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Prof. Dr. Pavel Kabat

Prof. Dr. Rik Leemans

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Dr. Fulco Ludwig

Dr. Robbert Biesbroek

Dr. Matti Kummu

Dr. Michelle T.H. van Vliet

I. General perspective on flood risk management and challenges

Q1. The Mekong delta has a long history of managing flood risk. To what extent do you agree with the following statement: "*Flood management in the Mekong delta has become more challenging compared to 30 years ago*"?

1. Fully agree
2. Agree
3. Neutral
4. Disagree
5. Strongly disagree
6. No answer

Q2. Literature has suggested several processes that make flood management more challenging. Based on your experience, please indicate the process(es) that make flood management in the Mekong delta more challenging compared to 30 years ago?

1. Climate change
2. Sea-level rise
3. Land use changes including deforestation in upstream countries
4. Hydropower dams construction in upstream countries
5. Population growth and urbanisation in upstream countries
6. Population growth and urbanisation in the Mekong delta
7. Dikes construction in the Mekong delta
8. Other process, namely: ....

Q3. Have you participated in any project concerning flood management in the Mekong delta? If yes, please give one project tittle.

Open answer: ....

II. Identifying important flood management challenges

Literature has identified many flood management challenges. They can be divided into three clusters, namely (i) *Knowledge and technical challenges*, (ii) *Institutional and governance challenges* and (iii) *resource challenges*. This section aims to find out the most important flood management challenges in the Mekong delta.

II-A. Technical challenges

Q4. Based on your experience, please indicate the importance of the following technical challenges in flood management in the Mekong delta? Please select the level of importance for each challenge.

G1 - Technical challenges	Very important	Important	Neutral	Unimportant	Very unimportant	No answer
C1: Lack of knowledge and understandings about the flood mechanisms in the floodplain						
C2: Existing flood protection measures create unintended impacts						
C3: Flood forecasting and early warning systems are not effective and reliable						
C4: Research results are not taken up in flood management processes						
C5: Local, indigenous knowledge is underused in flood management						
C6: Suitable strategies and measures for flood management are not available						
C7: Uncertainties in future climate change, sea-level rise and socio-economic development create difficulties for developing flood management plans						

II-B. Institutional and governance challenges

Q5. Based on your experience, please indicate the importance of the following institutional and governance challenges in flood management in the Mekong delta? Please select the level of importance for each challenge.

G2 - Institutional and governance challenges	Very important	Important	Neutral	Unimportant	Very unimportant	No answer
C8: Some factors causing flood are outside management boundary, i.e. in other country, province or district						
C9: Limited coordination and collaboration in flood management across provinces and districts						
C10: Conflicting interests between different management departments and regions						
C11: Flood and water management plans at different levels are inconsistent, leading to difficulties in implementation						
C12: Top-down, centralised approach to flood management						
C13: Flood management system is not responsive to new issues and challenges						

II-C. Resource challenges

Q6. Based on your personal experience, please indicate the importance of the following resource challenges in flood management in the Mekong delta? Please select the level of importance for each challenge.

G3 - Resource & Capacity challenges	Very important	Important	Neutral	Unimportant	Very unimportant	No answer
C14: Flood management lacks financial resource						
C15: Finance for flood management does not reach relevant regions and actors						
C16: Flood management staffs lack important capacities						
C17: Insufficient number of staffs for flood management						
C18: Lack of data and equipment for flood risk management						
C19: Limited institutional capacities for flood management, e.g. missing legislative instruments						

Q7. Apart from the above mentioned challenges, do you experience any other important flood management challenge(s)?

Open answer: ....

Q8. In previous questions, you have ranked the following challenges as important or very important. Please select <u>03 challenges</u> that you think are most important and thus need to be addressed so as to allow for improved flood risk management in the Mekong Delta.

Challenge 1 ◻

Challenge 2 ◻

...

Challenge n ◻

III. Explore solutions to address flood management challenges

In this section, we ask for your recommendations on solutions to overcome the most important flood management challenges in the Mekong delta.

Q9. In the previous step, you identified [FILL CHALLENGE] as one important flood management challenge. Could you please recommend two specific solutions, preferably with concrete examples, to overcome this challenge?

Open answer:

Solution 1: ....

Solution 2: ....

Q10. In the previous step, you identified [FILL CHALLENGE] as one important flood management challenge. Could you please recommend two specific solutions, preferably with concrete examples, to overcome this challenge?

Open answer:

Solution 1: ....

Solution 2: ....

Q11. In the previous step, you identified [FILL CHALLENGE] as one important flood management challenge. Could you please recommend two specific solutions, preferably with concrete examples, to overcome this challenge?

Open answer:

Solution 1: ....

Solution 2: ....

IV. Explore flood prevention measures

Flood risk can be mitigated through a number of flood prevention measures. In this section, we ask for your opinions on feasible infrastructure measures for flood prevention in the Mekong delta.

Q12. Based on your experience, please indicate which flood prevention measures are more relevant for the Mekong delta?

Flood prevention measures	Very relevant	Relevant	Neutral	Irrelevant	Very irrelevant	No answer
1. Controlled flooding in the Plain of Reeds and Long Xuyen Quadrangle. Agricultural land in these areas could be flooded to protect urbans.						
2. Full flood control for major cities and towns through improving and building new dikes.						
3. Creating retention zones and widen floodplains to store excessive flood water						
4. Improve existing flood water transfer capacity through river dredging, optimizing sluices/gates operation, etc.						
5. Build emergency flood diversion channels from Plain of Reeds and Long Xuyen Quadrangle to West and East Seas.						

Q13. Apart from the above mentioned measures, do you recommend any other infrastructure measures for flood protection in the Mekong delta?

Open answer: ....

V. Closing session

To finalise this survey, we would like to ask questions about your professional background. We only use the answers for analytical purpose and will only publish aggregated data.

Q14. Which of the below item best describe your occupation? Please select one item from the list below.

1. Government officer
2. Non-governmental organisation
3. Business/company
4. Social scientist
5. Natural scientist
6. Engineer
7. Other: ....

Q15. At which level is your work most focused on? Please select one item from the list below.

1. International
2. National
3. Regional (e.g. the Mekong delta)
4. Provincial
5. Municipal
6. Other: ....

Q16. Which of the following aspects of flood is your work most focused on? Please select one item from the list below

1. Flood research
2. Water management and planning
3. Land use management and planning
4. Flood protection infrastructures
5. Building flood resilience, living with flood
6. Climate change adaptation relating to flood
7. Flood early warning and emergency response
8. Other: ....

Q17. Is flood the most important component of your daily work?

1. Yes
2. No

Q18. What is your age category?

1. < 25 years old
2. 26 – 35 years old
3. 36 – 45 years old
4. 46 – 55 years old
5. 56 – 65 years old
6. > 65 years old

Q19. If you have any further comments/remarks about this questionnaire, please fill in the below lines.

....

Q20. You have finished our survey. We thank you very much for filling in the questionnaire!

Please indicate if you wish to receive the result of this survey:

1. Yes, please send results to ....

2. No thank you.

--------------------END-----------------------

Supplementary information G

Correlation coefficients between the challenges' rankings. C1 to C19 refer to flood management challenges listed in Table 5.1

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19
C1	1	0.02	0.21	0.12	0.12	-0.1	-0.09	0.09	-0	0.08	0.34**	0.02	0.17	-0	0.03	0.2	0.15	0.27*	0.04
C2		1	0.1	0.03	0.04	0.14	0	0.01	0.15	0.26*	0.28*	0.08	0.1	0.09	0.29*	0.03	-0.01	0.14	0.15
C3			1	0.09	0.2	0.26*	0.07	0.06	-0.1	-0.1	0.19	0	0.2	0.3*	0.18	0.28*	0.31**	0.29*	0.16
C4				1	0.17	0.03	0.02	-0	0.09	0.13	0.13	0.16	0.05	0	-0.1	-0.09	-0.11	0.12	0.06
C5					1	0.22	0.42**	0.07	0.29*	0.2	0.25*	0.35**	0.29*	-0	0.18	0.32**	0.2	0.38**	0.17
C6						1	0.46**	-0.1	0.19	0.12	0.16	0.17	0.01	0.2	0.17	0.12	0.04	0.33**	0.4**
C7							1	0.21	0.25*	0.13	0.19	0.04	0.26*	0.1	-0.1	0.3*	0.11	0.32**	0.29*
C8								1	-0.1	-0.04	0.12	0.19	0.33**	-0	-0	0.13	0.18	0.05	-0.07
C9									1	0.54**	0.35**	0.12	0.24*	0	0.26*	0.08	0.07	0.22	0.26*
C10										1	0.4**	0.12	0.18	0.01	0.38**	0.08	0.2	0.3	0.19
C11											1	0.13	0.13	0.18	0.2	0.32**	0.34**	0.44**	0.24*
C12												1	0.12	-0	0.08	-0.05	0.14	0.05	-0.05
C13													1	0.01	0.14	0.27*	0.13	0.21	0.23
C14														1	0.21	0.28*	0.47**	0.23	0.18
C15															1	0.29*	0.2	0.23	0.32**
C16																1	0.63**	0.42**	0.21
C17																	1	0.35**	0.24*
C18																		1	0.46**
C19																			1

**: Significant correlation at 0.95 confident level*

***: Significant correlation at 0.99 confident level*

Supplementary information H

Inventory of the measures to address flood management challenges

ID	Solutions	Recommendation frequency	Thematic strategy
1	Promote exchange and learning	24	Forster cross-boundary interactions
2	Implement integrated flood impact assessment	22	Improve data and decision support
3	Improve collaboration between actors	21	Forster cross-boundary interactions
4	Build capacity for flood management staff	21	Improve capacity and resources
5	Develop new technical measures	19	Innovate and shift flood management approaches
6	Improve communication	19	Forster cross-boundary interactions
7	Improve data sharing	16	Forster cross-boundary interactions
8	Improve collaboration between regions	15	Forster cross-boundary interactions
9	Revise existing measures	14	Strengthen and diversify the flood management portfolio
10	Improve human resources capacity	11	Improve capacity and resources
11	Promote participatory approach	11	Create an enabling environment for flood management
12	Promote integrated management	10	Strengthen and diversify the flood management portfolio
13	Develop new legislation	9	Create an enabling environment for flood management
14	Develop coordinating board	9	Create an enabling environment for flood management
15	Improve monitoring and early warning	9	Improve data and decision support
16	Shift thinking and management paradigm	8	Innovate and shift flood management approaches
17	Improve data's accuracy	8	Improve data and decision support
18	Improve coordination between regions	8	Create an enabling environment for flood management
19	Match expertise with problem	7	Improve capacity and resources
20	Generate funding from international collaboration	7	Improve capacity and resources
21	Improve institutional capacity	6	Improve capacity and resources
22	Improve coordination within region	6	Create an enabling environment for flood management
23	Develop agreements between regions	6	Create an enabling environment for flood management
24	Promote multi-objective flood management	6	Strengthen and diversify the flood management portfolio

25	Localize flood management	6	Strengthen and diversify the flood management portfolio
26	Set priorities in management	6	Strengthen and diversify the flood management portfolio
27	Improve flood modelling	5	Improve data and decision support
28	Generate funding from state budget	5	Improve capacity and resources
29	Diversify funding sources	5	Improve capacity and resources
30	Centralize flood management	5	Strengthen and diversify the flood management portfolio
31	Develop flood monitoring system	5	Improve data and decision support
32	Account for local conditions and resources	5	Improve capacity and resources
33	Invest in equipment	4	Improve capacity and resources
34	Develop education programs	4	Improve capacity and resources
35	Address unwanted impacts of existing measures	4	Strengthen and diversify the flood management portfolio
36	Enforce existing legislation	4	Create an enabling environment for flood management
37	Explore flood benefits	4	Strengthen and diversify the flood management portfolio
38	Synchronize flood monitoring, forecast and decision making	4	Improve data and decision support
39	Support stakeholders negotiation	4	Create an enabling environment for flood management
40	Adapt current policies	4	Innovate and shift flood management approaches
41	Resolve conflicts	4	Create an enabling environment for flood management
42	Promote integrated planning	4	Strengthen and diversify the flood management portfolio
43	Collect more data	4	Improve data and decision support
44	Test measures	4	Improve data and decision support
45	Develop visions	4	Strengthen and diversify the flood management portfolio
46	Improve coordination between actors	3	Create an enabling environment for flood management
47	Develop flood control system	3	Strengthen and diversify the flood management portfolio
48	Improve investment	3	Improve capacity and resources
49	Integrate multiple measures	3	Strengthen and diversify the flood management portfolio
50	Increase project funding	3	Improve capacity and resources
51	Develop adaptive measures	3	Strengthen and diversify the flood management portfolio
52	Publish research results	3	Improve data and decision support
53	Apply local knowledge in management	3	Strengthen and diversify the flood management portfolio
54	Compensate for negative management impacts	3	Strengthen and diversify the flood management portfolio

55	Improve training and education	3	Improve capacity and resources
56	Promote applied researches	2	Improve data and decision support
57	Promote flood-resilient development	2	Strengthen and diversify the flood management portfolio
58	Develop international agreements	2	Create an enabling environment for flood management
59	Optimize existing control infrastructures	2	Strengthen and diversify the flood management portfolio
60	Promote multi-level management	2	Strengthen and diversify the flood management portfolio
61	Improve planning	2	Strengthen and diversify the flood management portfolio
62	Raise awareness	2	Improve capacity and resources
63	Develop no-regret measures	2	Strengthen and diversify the flood management portfolio
64	Build bottom-up organisations	2	Strengthen and diversify the flood management portfolio
65	Localize flood research	2	Strengthen and diversify the flood management portfolio
66	Improve employment conditions	2	Improve capacity and resources
67	Improve transparency in management	2	Create an enabling environment for flood management
68	Establish flood research organisation	2	Improve data and decision support
69	Establish multi-stakeholder platform	2	Create an enabling environment for flood management
70	Develop alternative livelihoods	2	Innovate and shift flood management approaches
71	Improve data accessibility	2	Improve data and decision support
72	Adopt scenario-based planning	1	Strengthen and diversify the flood management portfolio
73	Apply international standards	1	Create an enabling environment for flood management
74	Avoid ineffective investment	1	Improve capacity and resources
75	Assess impacts of flood management	1	Improve data and decision support
76	Avoid technological lock-in	1	Strengthen and diversify the flood management portfolio
77	Develop early warning systems	1	Improve data and decision support
78	Create common understanding	1	Create an enabling environment for flood management
79	Develop data and information system	1	Improve data and decision support
80	Develop decision support system	1	Improve data and decision support
81	Combine forecast with indigenous knowledge	1	Improve data and decision support
82	Clarify responsibilities	1	Create an enabling environment for flood management
83	Compare measures	1	Improve data and decision support
84	Combine grant and loan in funding	1	Improve capacity and resources

85	Promote intermediary organisations	1	Forster cross-boundary interactions
86	Monitor implementation process	1	Improve data and decision support
87	Provide information to local level	1	Forster cross-boundary interactions
88	Provide demos and examples for proposed measures	1	Improve data and decision support
89	Match flood management with other objectives	1	Strengthen and diversify the flood management portfolio
90	Integrate multiple data sources	1	Improve data and decision support
91	Mitigate climate change	1	Strengthen and diversify the flood management portfolio
92	Match measures with available resources	1	Improve capacity and resources
93	Reduce population pressure	1	Strengthen and diversify the flood management portfolio
94	Set protection level	1	Strengthen and diversify the flood management portfolio
95	Set priorities in funding	1	Improve capacity and resources
96	Upgrade and maintain existing infrastructures	1	Strengthen and diversify the flood management portfolio
97	Shift power balance between actors	1	Create an enabling environment for flood management
98	Separate flood management from other objectives	1	Innovate and shift flood management approaches
99	Remove institutional barriers	1	Create an enabling environment for flood management
100	Set priorities for most vulnerable regions	1	Strengthen and diversify the flood management portfolio
101	Separate technical and managerial training	1	Innovate and shift flood management approaches
102	Implement and enforce existing plans	1	Strengthen and diversify the flood management portfolio
103	Improve flood emergency responses	1	Strengthen and diversify the flood management portfolio
104	Improve financial resources	1	Improve capacity and resources
105	Idenfity knowledge demands	1	Improve data and decision support
106	Focus research on basin-wide issues	1	Improve data and decision support
107	Evaluate quality of research results	1	Improve data and decision support
108	Focus training and education on the junior staff	1	Improve capacity and resources
109	Focus research on local issues	1	Improve data and decision support
110	Improve research funding	1	Improve capacity and resources
111	Improve measures applicability	1	Strengthen and diversify the flood management portfolio
112	Improve knowledge uptake	1	Improve data and decision support
113	Improve independence of legal institutions	1	Create an enabling environment for flood management
114	Improve recruitment	1	Improve capacity and resources

Supplementary information I

Flood management strategies and associated measures

Strategy S1: Create an enabling environment for flood management		
Member solutions	**Recommendation frequency**	**Solution ID**
Promote participatory approach	11	11
Develop new legislation	9	13
Develop coordinating board	9	14
Improve coordination between regions	8	18
Improve coordination within region	6	22
Develop agreements between regions	6	23
Enforce existing legislation	4	36
Support stakeholders negotiation	4	39
Resolve conflicts	4	41
Improve coordination between actors	3	46
Develop international agreements	2	58
Improve transparency in management	2	67
Establish multi-stakeholder platform	2	69
Apply international standards	1	73
Create common understanding	1	78
Clarify responsibilities	1	82
Shift power balance between actors	1	97
Remove institutional barriers	1	99
Improve independence of legal institutions	1	113

Strategy S2: Strengthen and diversify the flood management portfolio		
Member solutions	**Recommendation frequency**	**Solution ID**
Revise existing measures	14	9
Promote integrated management	10	12
Promote multi-objective flood management	6	24
Localize flood management	6	25
Set priorities in management	6	26
Centralize flood management	5	30
Address unwanted impacts of existing measures	4	35
Explore flood benefits	4	37
Promote integrated planning	4	42
Develop visions	4	45
Develop flood control system	3	47
Integrate multiple measures	3	49
Develop adaptive measures	3	51
Apply local knowledge in management	3	53
Compensate for negative management impacts	3	54
Promote flood-resilient development	2	57
Optimize existing control infrastructures	2	59
Promote multi-level management	2	60

Improve planning	2	61
Develop no-regret measures	2	63
Build bottom-up organisations	2	64
Localize flood research	2	65
Adopt scenario-based planning	1	72
Avoid technological lock-in	1	76
Match flood management with other objectives	1	89
Mitigate climate change	1	91
Reduce population pressure	1	93
Set protection level	1	94
Upgrade and maintain existing infrastructures	1	96
Set priorities for most vulnerable regions	1	100
Implement and enforce existing plans	1	102
Improve flood emergency responses	1	103
Improve measures applicability	1	111

Strategy S3: Forster cross-boundary interactions

Member solutions	Recommendation frequency	Solution ID
Promote exchange and learning	24	1
Improve collaboration between actors	21	3
Improve communication	19	6
Improve data sharing	16	7
Improve collaboration between regions	15	8
Promote intermediary organisations	1	85
Provide information to local level	1	87

Strategy S4: Improve capacity and resources

Member solutions	Recommendation frequency	Solution ID
Build capacity for flood management staff	21	4
Improve human resources capacity	11	10
Match expertise with problem	7	19
Generate funding from international collaboration	7	20
Improve institutional capacity	6	21
Generate funding from state budget	5	28
Diversify funding sources	5	29
Account for local conditions and resources	5	32
Invest in equipment	4	33
Develop education programs	4	34
Improve investment	3	48
Increase project funding	3	50
Improve training and education	3	55
Raise awareness	2	62
Improve employment conditions	2	66
Avoid ineffective investment	1	74
Combine grant and loan in funding	1	84

Match measures with available resources	1	92
Set priorities in funding	1	95
Improve financial resources	1	104
Focus training and education on the junior staff	1	108
Improve research funding	1	110
Improve recruitment	1	114

Strategy S5: Improve data and decision support		
Member solutions	**Recommendation frequency**	**Solution ID**
Implement integrated flood impact assessment	22	2
Improve monitoring and early warning	9	15
Improve data's accuracy	8	17
Improve flood modelling	5	27
Develop flood monitoring system	5	31
Synchronize flood monitoring, forecast and decision making	4	38
Collect more data	4	43
Test measures	4	44
Publish research results	3	52
Promote applied researches	2	56
Establish flood research organisation	2	68
Improve data accessibility	2	71
Assess impacts of flood management	1	75
Develop early warning systems	1	77
Develop data and information system	1	79
Develop decision support system	1	80
Combine forecast with indigenous knowledge	1	81
Compare measures	1	83
Monitor implementation process	1	86
Provide demos and examples for proposed measures	1	88
Integrate multiple data sources	1	90
Identify knowledge demands	1	105
Focus research on basin-wide issues	1	106
Evaluate quality of research results	1	107
Focus research on local issues	1	109
Improve knowledge uptake	1	112

Strategy 6: Innovate and shift approaches		
Membering solutions	**Recommendation frequency**	**Solution ID**
Develop new technical measures	19	5
Shift thinking and management paradigm	8	16
Adapt current policies	4	40
Develop alternative livelihoods	2	70
Separate flood management from other objectives	1	98
Separate technical and managerial training	1	101

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Summary

The Mekong – largest river in Southeast Asia, represents a globally significant river in terms of climate-change vulnerability and rapidly increasing human pressures on water resources. The river's transboundary flows greatly support livelihoods of millions of people and provide important water resources for various economic sectors including agriculture, fishery and hydropower production. However, climate change and accelerating socioeconomic developments are expected to cause substantial hydrological changes (i.e. changing flow regime and hydrological extremes), thereby posing critical challenges for water-related safety and water resources sustainability. Despite recently growing research interests, projected hydrological changes are highly uncertain and little attention has been paid to hydrological extremes. Additionally, anticipatory adaptation to future changes remains highly challenging due to underdeveloped adaptation interventions. This multidisciplinary study therefore quantifies future changes in the Mekong's future flow regime and hydrological extremes and subsequently develops adaptation measures and strategies to adapt to the associated risks.

This study first assessed climate change impacts on the Mekong's flow regime with specific focus on changes in extreme high flow and low flow conditions (Chapter 2). River flows were simulated with the VMod hydrological model, using a large ensemble of downscaled and bias corrected climate change scenarios from five General Circulation Models and two Representative Concentration Pathways (i.e. RCP4.5 and RCP8.5). Results showed substantial increases in seasonal and annual flows (between +5% and +16%, annually) in all mainstream stations, with slight reductions (up to -7%) during the early wet season (i.e. June - July). Regarding hydrological extremes, high flows during the wet season will increase in both magnitudes and frequencies, implying higher flood risks. On the other hand, water availability during the dry season may increase due to overall higher river flows. Furthermore, hydrological impact signals from this study are more robust than those reported in earlier studies, which were based on the Coupled Model Intercomparison Project phase 3 - CMIP3 projections. While the uncertainty range of projected hydrological impact signals reduces substantially, cross-scenario agreements on directional changes improve markedly compared to earlier studies. Robust hydrological change signals reinforce the needs for more detailed impact quantifications including future floods and for effective adaptive interventions.

In a next step, a scenario-based hydrological impact assessment was implemented to assess future hydrological changes under the combined impacts of climate change and key human development activities (Chapter 3). A newly developed crop and irrigation module, and a hydropower dam operation module were coupled into the VMod hydrological model to simulate river flows under multiple scenarios of future climate change, irrigation expansions and hydropower developments. Results demonstrated the Mekong's high degrees of susceptibility to the considered driving factors. Future flow regime shows substantial changes, characterized by (1) consistent dry season flow increases, up to +150% and (2) contrasting flow reductions (up to -25% during June - October) and flow increases (up to +36% during November - December). Flow changes are driven by both impact compensation (e.g. climate change induced flow increases are mitigated by dams operation during the late wet season) and impact exacerbation (e.g. accumulated flow reductions caused by all drivers during the early wet season). Insights from this study contribute to improved understanding about the magnitude and complex mechanisms of future hydrological changes under multiple driving factors. Future flow changes can affect economic activities, increase safety risks, affect local livelihoods and damage ecosystem dynamics, thus emphasizing the needs for assessing future developments' hydrological impacts and for adequate adaptive interventions.

Next, this study quantified future flood hazards under both upstream hydrological changes and downstream sea level rise for the Mekong Delta (Chapter 4). The low-lying Mekong Delta has long been identified as one of the world's most vulnerable river deltas to climate change and sea level rise, however quantifications of future impacts including extreme floods remains very limited. A model chain was developed by linking a multi-site weather generator, the VMod hydrological model, and the Mekong Delta flood model to simulate extreme floods under 'high-end' climate change (i.e. RCP8.5) and sea level rise scenarios. Results showed significant increases in flood hazards throughout the whole Mekong Delta. Increasing extreme floods are characterized by higher flood frequencies and magnitudes, where flood depths could increase of up to +0.9 m under the future 500-year flood events. Additionally, upstream hydrological changes and sea level rise exhibit distinct spatial distributions of their impacts. While higher upstream inflows mostly increase floods in the upper delta, sea level rise causes higher flood hazards in the middle and coastal delta. All in all, increasing future floods poses critical safety risks for local inhabitants and infrastructures, thus requiring better flood protection and more flood resilient developments.

Finally, a multidisciplinary adaptation appraisal was implemented to develop measures and strategies to adapt to future hydrological changes, focusing on extreme floods in the Mekong Delta (Chapter 5). Increasing flood risks represent a critical challenge for water-related safety and sustainable developments in the Mekong Delta, however the question of how to effectively adapt to future floods remain largely unaddressed. To develop adaptation measures and strategies, relevant data were collected from a systematic literature review and expert surveys and then analysed using novel analyses involving both qualitative (i.e. content analysis) and quantitative method (i.e. statistical inference). A total of 114 adaptation measures were developed and combined into six strategies, namely (S1) Create a more enabling environment for flood management; (S2) Strengthen and diversify the flood management portfolio; (S3) Foster cross-boundary interactions; (S4) Improve capacity and resources; (S5) Improve data and decision support; and (S6) Innovate and shift flood management approaches. Results show that effective adaptation to future flood requires looking beyond the conventional management approach, which focuses strongly on technical fixes. Instead, integrating multiple innovative solutions, combined with suitable governance and institutional settings offer great opportunities to minimize flood risks under climate change and accelerating socioeconomic developments.

This study shows substantial impacts of climate change and accelerating socioeconomic development activities on the Mekong River's flows, characterized by changing seasonal flow dynamics and increasing hydrological extremes across the basin. Additionally, extreme floods in the Mekong Delta are projected to increase significantly, posing critical challenges for safety and sustainable developments. Despite great challenges associated with the projected hydrological changes, this study also demonstrated that managing future changes are feasible through strategic development planning and through adaptive interventions. Furthermore, this study offers concrete measures and strategies for adaptation to hydrological changes, focusing on future floods in the Mekong Delta as a key vulnerability hotspot. Future hydrological changes and associated risks under climate change and accelerating socioeconomic developments represent one of the most important challenges for the Mekong region during the 21st century. Proper quantifications of future changes and effective responses are therefore highly important to ensure a safe Mekong River with undisrupted and fair provisions of critical values for the region's economies, its people and its unique natural ecosystems.

Samenvatting

De Mekong is de grootste rivier van zuidoost Azië en wordt wereldwijd beschouwd als een belangrijke rivier vanwege haar kwetsbaarheid voor klimaatverandering en de snel groeiende menselijke activiteiten die de druk op het watersysteem versterken. Miljoenen mensen zijn afhankelijk van het water van deze grensoverschrijdende rivier voor economische activiteiten zoals landbouw, visserij en elektriciteitsproductie vanuit waterkracht. Klimaatverandering en socio-economische veranderingen zullen echter belangrijke hydrologische gevolgen hebben (d.w.z. verandering in afvoerregime en hydrologische extremen) wat een uitdaging kan vormen voor de waterzekerheid en duurzaamheid. Ondanks recente toename in onderzoek naar de Mekong zijn er nog steeds grote onzekerheden in de geprojecteerde hydrologische veranderingen en wordt er nog weinig aandacht besteed aan de gevolgen voor hydrologische extremen. Daarnaast zijn anticipatieve aanpassingen aan toekomstige veranderingen nog steeds een grote uitdaging vanwege beperkt ontwikkelde adaptatie interventies. Deze multidisciplinaire studie richt zich daarom op het kwantificeren van toekomstige veranderingen in afvoerregime en hydrologische extremen van de Mekong, samen met de ontwikkeling van adaptatiemaatregelen en -strategieën om aan deze risico's aan te passen.

Eerst is gekeken naar de effecten van klimaatverandering op het afvoerregime en veranderingen in extreem hoge en lage rivierafvoeren van de Mekong (Hoofdstuk 2). Rivierafvoer was gesimuleerd met het VMod hydrologisch model door gebruik te maken van een groot ensemble van gedownscaled en bias-gecorrigeerde klimaatscenario's van vijf mondiale klimaatmodellen (General Circulation Models) en twee scenario's voor toekomstige broeikasgasconcentraties (Representative Concentration Pathways) namelijk RCP4.5 en RCP8.5. De resultaten tonen een substantiële toename in seizoenale en jaarlijkse afvoer (jaargemiddeld tussen +5% en +16%) voor alle hoofdstations en een lichte afname (tot 7%) tijdens het natte seizoen (d.w.z. juni-juli). De frequentie en intensiteit van hoge afvoeren tijdens het natte seizoen zullen toenemen, en dit kan tot een toename in overstromingsrisico's leiden. Waterbeschikbaarheid tijdens het droge seizoen zal toenemen ten gevolge van een stijging in rivierafvoer. De geprojecteerde veranderingen in hydrologie zijn meer robuust dan de resultaten van eerdere studies die gebaseerd zijn op het Coupled Model Intercomparision Project phase 3 (CMIP3). Dit blijkt uit een afname in bandbreedte van onzekerheden tussen de scenario's en een toename in overeenstemming van de richting van hydrologische veranderingen uit dit onderzoek ten opzichte van eerdere studies. Robuuste hydrologische veranderingen benadrukken het belang van gedetailleerde impactstudies om toekomstige hoge rivierafvoeren beter te kwantificeren en effectieve adaptatiemaatregelen te ontwikkelen.

In een vervolgstap zijn toekomstige hydrologische veranderingen als gevolg van gecombineerde effecten van klimaatverandering en menselijke activiteiten doorgerekend (Hoofdstuk 3). Voor deze scenario-impact studie zijn een gewas- en irrigatiemodule en een waterkracht-dammodule ontwikkeld en gekoppeld aan het VMod hydrologisch model om op die manier rivierafvoer te kunnen simuleren onder verschillende scenario's van toekomstig klimaat, irrigatie-expansie en waterkrachtontwikkeling. De resultaten tonen dat het afvoerregime van de Mekong in sterke mate beïnvloed zal worden door deze ontwikkelingen met substantiële veranderingen gekarakteriseerd door: (1) consistente toenamen (tot 150%) in rivierafvoer tijdens het droge seizoen en (2) contrasterende afnamen (tot -25% tijdens juni-oktober) en toenamen in rivierafvoer (tot +36% tijdens november-december). Deze hydrologische veranderingen zijn gedreven door zowel compensatie van effecten (bv. toenamen in afvoer geïnduceerd door klimaatverandering worden gemitigeerd door operationeel management van dammen tijdens het laat natte seizoen) en versterking van effecten (bv. accumulatie van afnamen in rivierafvoer tijdens het vroeg natte seizoen veroorzaakt door alle ontwikkelingen). Inzichten van deze studie dragen bij aan verbeterde kennis over complexe mechanismen van toekomstige hydrologische veranderingen onder verschillende ontwikkelingen. Toekomstige veranderingen in rivierafvoer kunnen economische activiteiten en lokale bestaansmiddelen beïnvloeden, veiligheidsrisico's doen toenemen en mogelijk schade toebrengen aan ecosysteemdynamiek. Dit benadrukt het belang van adequate adaptieve interventies om hydrologische effecten onder verschillende toekomstige ontwikkelingen beter te beheren.

In een volgende stap zijn voor de Mekong Delta overstromingsrisico's doorgerekend ten gevolge van zowel bovenstroomse hydrologische veranderingen onder veranderend klimaat als benedenstroomse zeespiegelstijging (Hoofdstuk 4). Hoewel de laaggelegen Mekong Delta wordt beschouwd als een van de meest kwetsbare rivierdelta's voor klimaatverandering en zeespiegelstijging, waren er voorheen nog weinig kwantitatieve effecten doorgerekend. Een modelketen is gebruikt, bestaande uit een weergenerator (voor meerdere locaties), het VMod hydrologisch model en het Mekong Delta overstromingsmodel, om extreme overstromingen te kunnen simuleren voor de meest sterke scenario's van klimaatverandering (RCP8.5) en zeespiegelstijging. De resultaten tonen significante toenamen in overstromingsrisico's in de gehele Mekong Delta. Deze worden gekarakteriseerd door toenamen in de frequentie en magnitude van overstromingen. Bij toekomstige overstromingen met een herhalingstijd van 500 jaar kan de overstromingsdiepte toenemen tot +0.9 m. De effecten van bovenstroomse hydrologische veranderingen en zeespiegelstijging tonen echter ruimtelijke verschillen. Stijging in bovenstroomse afvoeren in de Mekong rivier zullen vooral in het bovenstroomse deel van de delta invloed hebben, terwijl zeespiegelstijging met name in het midden- en kustdeel van de delta de overstromingsrisico's zal vergroten. De gesimuleerde toenamen in overstromingen in de Mekong Delta zullen leiden tot toenamen in kritieke veiligheidsrisico's voor lokale inwoners en infrastructuur, wat vraagt om betere bescherming en veerkrachtige maatregelen tegen overstromingen.

Tot slot is er een multidisciplinaire adaptatiebeoordelingsstudie uitgevoerd met het doel om maatregelen en strategieën te ontwikkelen om aan te passen aan toekomstige hydrologische veranderingen en overstromingsrisico's in de Mekong Delta (Hoofdstuk 5). Toenamen in overstromingsrisico's zijn een uitdaging voor water-gerelateerde veiligheid en duurzame ontwikkelingen in de Mekong Delta. Echter, de vraag hoe effectief aan te passen aan toekomstige overstromingen bleef voorheen grotendeels onbeantwoord. In deze studie zijn relevante data verzameld uit systematisch literatuuronderzoek en enquêtes met experts. Deze zijn vervolgens geanalyseerd met innovatieve analysemethoden die zowel kwalitatieve (d.w.z. inhoudelijke analyses) als kwantitatieve (d.w.z. statistische analyse) methoden omvatten. In totaal zijn 114 adaptatiemaatregelen ontwikkeld en gecombineerd in zes strategieën, namelijk (S1) Creëren van een verbeterde omgeving voor overstromingsmanagement; (S2) Versterken en diversifiëren van overstromingsmanagement portfolio; (S3) Bevorderen van grensoverschrijdende interacties; (S4) Verbetering van capaciteit en bronnen; (S5) Verbeteren van data en ondersteuning voor besluitvorming; (S6) Innoveren en verschuiven van overstromingsmanagement benaderingen. De resultaten tonen dat effectieve adaptatie aan toekomstige overstromingen vraagt om verder te kijken dan conventionele overstromingsmaatregelen waarbij de focus sterk ligt op technische verbeteringen. In plaats hiervan zou het integreren van meerdere innovatieve oplossingen, gecombineerd met geschikte bestuurlijke en institutionele benaderingen betere perspectieven kunnen bieden om overstromingsrisico's ten gevolge van klimaatverandering en socio-economische ontwikkelingen te minimaliseren.

Deze studie laat zien dat klimaatverandering en socio-economische ontwikkelingen substantiële effecten zullen hebben op de afvoer van de Mekong rivier, met veranderingen in seizoenale afvoerdynamiek en toenamen in hydrologische extremen. Daarnaast tonen de modelresultaten een toename in extreme overstromingen in de Mekong Delta, wat de toekomstige waterzekerheid en duurzame ontwikkelingen kan belemmeren. Ondanks de grote uitdagingen gepaard met deze verwachte hydrologische veranderingen, laat deze studie ook de haalbaarheid zien van verbeterd waterbeheer door strategische ontwikkeling en adaptieve interventies. Bovendien toont deze studie concrete maatregelen en strategieën voor aanpassingen aan hydrologische veranderingen en overstromingen waarbij gericht is op de Mekong Delta als de meest kwetsbare regio ('hotspot'). Toekomstige hydrologische veranderingen onder veranderend klimaat en socio-economische ontwikkelingen en de daarmee verbonden risico's zijn een van de belangrijkste uitdagingen voor de Mekong in de 21ste eeuw. Goede kwantificatie van deze toekomstige veranderingen en effectieve maatregelen zijn daarom van groot belang om de veiligheid en een eerlijke waterverdeling van de Mekong voor haar regionale economieën, inwoners en unieke natuurlijke ecosystemen te kunnen garanderen.

Tóm tắt nghiên cứu

Mekong là dòng sông quốc tế với diện tích lưu vực lớn nhất khu vực Đông Nam Á. Lưu vực sông Mekong còn có ý nghĩa quan trọng toàn cầu về các tác động của biến đổi khí hậu, đặc biệt là khu vực hạ lưu Mekong- đồng bằng sông Cửu Long. Đồng thời, đây còn là điểm nóng về ảnh hưởng ngày càng gia tăng của các hoạt động phát triển kinh tế xã hội lên chế độ thủy văn và tài nguyên nước. Dòng chảy xuyên quốc gia của sông Mekong có nhiều ý nghĩa to lớn đối với sinh kế của hàng triệu cư dân, cũng như cung cấp nguồn tài nguyên nước cho hàng loạt các hoạt động phát triển kinh tế, bao gồm nông nghiệp, thủy sản và năng lượng thủy điện. Tuy nhiên, biến đổi khí hậu kèm theo gia tăng các hoạt động phát triển kinh tế gần đây có nguy cơ gây ra các thay đổi lớn trong chế độ thủy văn sông Mekong (thay đổi trong đặc thù dòng chảy, và dòng chảy cực đoan), từ đó tạo ra các thách thức to lớn trong kiểm soát rủi ro liên quan tới lũ lụt, hạn hán, và trong duy trì sử dụng tài nguyên nước một cách bền vững. Mặc dù các nghiên cứu gần đây khá chú trọng tới vùng sông Mekong, các nghiên cứu về thay đổi dòng chảy cực đoan hiện nay vẫn còn nhiều hạn chế. Hơn nữa, các kết quả dự báo thay đổi dòng chảy trong tương lai còn có tính bất định cao. Thêm vào đó, việc chủ động thích ứng với các tác động của biến đổi khí hậu còn là một thách thức lớn, do các nỗ lực nghiên cứu phát triển các biện pháp thích ứng còn chưa được chú trọng đúng mức. Trong bối cảnh đó, nghiên cứu liên nghành này tập trung mô phỏng và lượng hóa các thay đổi trong chế độ thủy văn (trong đó có dòng chảy cực đoan) sông Mekong, từ đó phát triển các giải pháp và chiến lược nhằm thích ứng với các rủi ro và thách thức liên quan.

Báo cáo nghiên cứu gồm có 6 chương, trong đó nội dung chính được trình bày từ Chương 2 đến Chương 5. Chương 2 trình bày kết quả nghiên cứu đánh giá các tác động của biến đổi khí hậu lên chế độ thủy văn sông Mekong, trong đó tập trung vào các thay đổi đối với dòng chảy lũ, và dòng chảy kiệt. Dòng chảy trong sông được mô phỏng với mô hình thủy văn VMod, sử dụng một bộ các kịch bản biến đổi khí hậu đã được chi tiết hóa và hiệu chỉnh sai số, dựa trên 05 mô hình khí hậu toàn cầu và 02 kịch bản biến đổi khí hậu (RCP4.5 và RCP8.5). Kết quả mô phỏng thủy văn dự báo gia tăng đáng kể trong dòng chảy năm và dòng chảy mùa (dòng chảy năm gia tăng giữa +5% và +16%), tại tất cả các trạm thủy văn chính trên toàn lưu vực. Tuy nhiên, kết quả dự báo cho thấy dòng chảy trong giai đoạn đầu mùa mưa (Tháng 6 - 7) sẽ giảm nhẹ (tối đa -7%). Đối với dòng chảy cực đoan, dòng chảy lũ được dự báo sẽ tăng cao cả về tần suất và biên độ, dẫn tới gia tăng nguy cơ xảy ra lũ lớn. Đồng thời, trữ lượng tài nguyên nước trong mùa khô được dự báo sẽ được tăng cường nhờ có gia tăng trong dòng chảy mùa kiệt. Đáng lưu ý là kết quả dự báo thay đổi dòng chảy trong nghiên cứu này có độ tin cậy cao hơn so với các kết quả nghiên cứu trước đó, vốn dựa trên các kịch bản khí hậu từ chương trình *Coupled Model Intercomparison Project phase 3 - CMIP3*. Cụ thể, khoảng bất định (*ensemble''s uncertainty range*) đối với dự báo dòng chảy trong nghiên cứu này giảm đáng kể, đồng thời kết quả dự báo giữa các kịch bản biến đổi khí hậu có mức độ đồng thuận tốt. Các kết quả dự báo chế độ thủy văn cho vùng Mekong nhấn mạnh tầm quan trọng và tính cấp

thiết của việc chi tiết hóa các dự báo cho lũ lụt, đồng thời nghiên cứu phát triển các giải pháp nhằm thích ứng một cách hiệu quả.

Chương 3 tập trung đánh giá tác động cộng gộp của biến đổi khí hậu và các hoạt động phát triển kinh tế xã hội lên chế độ thủy văn toàn lưu vực Mekong. Một mô-đun phục vụ mô phỏng phát triển cây nông nghiệp và tưới tiêu, và một mô-đun mô phỏng vận hành hồ chứa thủy điện được phát triển mới và tích hợp vào mô hình thủy văn VMod, nhằm mô phỏng dòng chảy trong điều kiện biến đổi khí hậu, gia tăng diện tích đất nông nghiệp và phát triển thủy điện trên toàn bộ lưu vực. Kết quả mô hình cho thấy mức độ nhạy cảm cao của chế độ dòng chảy Mekong trong các kịch bản gia tăng hoạt động nông nghiệp và vận hành hồ chứa theo mục tiêu tối đa sản lượng điện. Cụ thể, chế độ dòng chảy sẽ có nhiều thay đổi lớn, bao gồm (1) tăng cao dòng chảy các tháng mùa kiệt, tối đa tới +150%, và (2) trong khi dòng chảy các tháng VI – tháng X giảm (tối đa -25%); dòng chảy các tháng XI-XII có xu hướng tăng, tối đa +36%. Thay đổi chế độ dòng chảy bị chi phối bởi hiện tượng bù trừ tác động (vd: trong các tháng nửa cuối mùa lũ, gia tăng dòng chảy lũ do biến đổi khí hậu được bù trừ một phần bởi các hồ chứa thủy điện) và hiện tượng tăng cường tác động (vd: dòng chảy đầu mùa lũ suy giảm đáng kể do biến đổi khí hậu, tưới tiêu và hồ chứa thủy điện đồng loạt làm giảm dòng chảy). Các kết quả trong chương này góp phần làm sáng tỏ bản chất, cơ chế phức tạp, đồng thời lượng hóa các thay đổi dòng chảy trên lưu vực Mekong dưới tác động cộng gộp của nhiều yếu tố chi phối. Thay đổi dòng chảy sông Mekong trong tương lai sẽ có nhiều tác động quan trọng tới sinh kế người dân cũng như các hệ sinh thái tự nhiên, do đó nhu cầu nghiên cứu lượng hóa và phát triển giải pháp thích ứng là hết sức cấp thiết.

Chương 4 tập trung mô phỏng và lượng hóa lũ lớn tại vùng đồng bằng sông Cửu Long dưới tác động của thay đổi chế độ dòng chảy từ thượng lưu và nước biển dâng. Mặc dù vùng đồng bằng sông Cửu Long từ lâu đã được nhận định là một trong các vùng châu thổ sẽ bị ảnh hưởng rất lớn do biến đổi khí hậu và nước biển dâng, tuy nhiên các nghiên cứu giúp lượng hóa tác động (bao gồm tác động lên chế độ lũ) còn thiếu. Nghiên cứu này xây dựng một tổ hợp mô hình dựa trên việc liên kết các hợp phần: mô hình mô phỏng số liệu khí hậu đa điểm (*stochastic multi-site weather geneator*), mô hình thủy văn VMod, và mô hình lũ cho vùng đồng bằng sông Cửu Long; phục vụ mô phỏng lũ trong các kịch bản cao về biến đổi khí hậu (kịch bản RCP8.5) và nước biển dâng. Kết quả nghiên cứu cho thấy các mức gia tăng mạnh trong tai biến lũ trên toàn vùng đồng bằng sông Cửu Long. Gia tăng tai biến lũ được thể hiện qua gia tăng tần suất lũ lớn, cũng như biên độ lũ, với biên độ lũ cực đại tăng tới +0.9m trong các trận lũ với tần suất 500 năm. Thêm vào đó, thay đổi chế độ dòng chảy từ thượng lưu và nước biển dâng tác động tới các vùng khác nhau trong vùng đồng bằng sông Cửu Long. Kết quả mô hình cho thấy trong khi thay đổi dòng chảy thượng lưu ảnh hưởng nhiều tới lũ tại vùng Tứ Giác Long Xuyên và Đồng Tháp Mười; nước biển dâng có xu hướng ảnh hưởng nhiều tới các vùng hạ châu thổ và dọc ven biển. Gia tăng mạnh trong tai biến lũ tạo ra các thách thức lớn đối với an toàn lũ cho người dân và các cơ sở hạ tầng, do đó nhấn mạnh vai trò thiết yếu của các công trình kiểm soát lũ cũng như các giải pháp phát triển hài hòa với lũ lớn ở vùng đồng bằng sông Cửu Long.

Chương 5 trình bày một nghiên cứu liên nghành nhằm phát triển các giải pháp thích ứng với các thay đổi trong chế độ thủy văn, trong đó tập trung vào thích ứng với lũ lớn tại vùng đồng bằng sông Cửu Long. Gia tăng tai biến lũ là một trong các thách thức quan trọng nhất đối với sự an toàn và phát triển bền vững cho vùng đồng bằng sông Cửu Long, do vậy việc nghiên cứu giải pháp thích ứng đang được đặt ra như một nhu cầu hết sức cấp thiết. Nhằm phát triển các giải pháp và chiến lược thích ứng, nghiên cứu này trước hết thu thập số liệu dựa trên khảo cứu tài liệu, và tham vấn ý kiến chuyên gia. Số liệu thu thập được sau đó được phân tích dựa trên một phương pháp phân tích tích hợp, trong đó sử dụng phân tích định tính (vd: phương pháp phân tích nội dung – content analysis) và phân tích định lượng (vd: các phương pháp phân tích thống kê). Nghiên cứu này phát triển 6 chiến lược chung phục vụ thích ứng với lũ cho vùng đồng bằng sông Cửu Long, trong đó tích hợp 114 giải pháp cụ thể. Các chiến lược bao gồm: S1 - Xây dựng một môi trường quản lý phù hợp hơn cho quản lý lũ; S2 - Tăng cường hiệu quả và đa dạng hóa các phương án kiểm soát lũ; S3 - Tăng cường tương tác liên nghành và liên vùng; S4 - Xây dựng năng lực và tài nguyên phục vụ quản lý lũ; S5 - Cải thiện số liệu và thông tin phục vụ công tác ra quyết định; và S6 - Xây dựng các giải pháp mới giúp chuyển hướng phương pháp quản lý lũ. Nghiên cứu này cũng cho thấy quản lý lũ trong bối cảnh mới ở vùng đồng bằng sông Cửu Long yêu cầu cần cải tiến phương án quản lý hiện thời, vốn tập trung nhiều vào các giải pháp công trình. Thay vào đó, việc kết hợp một cách thích hợp các giải pháp công trình mới kèm theo hoàn thiện các chính sách quản lý và cải thiện thể chế có vai trò to lớn trong việc giảm thiểu rủi ro lũ trong bối cảnh biến đổi khí hậu và phát triển kinh tế xã hội ngày càng nhanh.

Nghiên cứu này xác định và lượng hóa các tác động quan trọng của biến đổi khí hậu và các hoạt động phát triển kinh tế xã hội lên chế độ thủy văn sông Mekong, trong đó tập trung vào thay đổi chế độ dòng chảy theo mùa, và gia tăng các hiện tượng thủy văn cực đoan trên toàn lưu vực. Đồng thời, kết quả nghiên cứu cho thấy lũ lớn ở vùng đồng bằng sông Cửu Long cũng có xu hướng gia tăng mạnh, gây ra các thách thức to lớn cho an toàn lũ và phát triển bền vững. Bên cạnh việc chỉ ra các mối thách thức liên quan tới thay đổi chế độ thủy văn sông Mekong, nghiên cứu này cũng cho thấy việc quản lý và thích ứng với các thay đổi đó có thể được thực hiện dựa trên việc lập kế hoạch phát triển toàn lưu vực và triển khai các giải pháp thích ứng cụ thể. Thêm vào đó, nghiên cứu này cũng tập trung xây dựng và đề xuất các chiến lược và biện pháp cụ thể phục vụ thích ứng với lũ ở vùng đồng bằng sông Cửu Long, trong bối cảnh biến đổi khí hậu, nước biển dâng và phát triển kinh tế xã hội ở vùng thượng lưu. Các thay đổi về chế độ thủy văn và các mối nguy cơ liên quan đang được đặt ra như là một thách thức quan trọng hàng đầu đối với cư dân và các nền kinh tế thành viên trong lưu vực sông Mekong. Thông tin lượng hóa chính xác cũng như các giải pháp quản lý hiệu quả sẽ là chìa khóa giúp quản lý hiệu quả các thay đổi trong chế độ thủy văn và tài nguyên nước trên lưu vực sông Mekong, hướng tới một dòng sông quốc tế có độ an toàn thủy cao, với các giá trị tài nguyên nước, sinh thái và kinh tế được duy trì và chia sẻ một cách bền vững.

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Amsterdam, 20 February 2017

Your Long

Curriculum Vitae

Long Phi Hoàng was born on 20th February 1987 in Sapa (ca. 1500 masl), Vietnam. He later moved to Hanoi to study English, Biology, and Environmental Sciences. In 2009, he graduated with distinction from Hanoi University of Science and continued with his MSc study focusing on Integrated Water Management and Climate Change at Wageningen University, the Netherlands. He wrote his MSc thesis on how to define and assess adaptive capacity for climate change adaptation in the water management contexts and graduated with distinction in 2011. Shortly after graduation, Long joined the Wageningen team to work on the Dutch-Vietnamese collaborative project to develop the Mekong Delta Plan (2011-2012). This work exposed him to some key concepts of strategic delta planning, climate proofing, scenario assessments and quantifications, which later became the key elements of his PhD research.

Long started his PhD in the Water Systems and Global Change Group (back then Earth System Science), Wageningen University in 2013. During his PhD, he travelled to the Mekong Delta in Vietnam and several other countries for fieldtrips, conferences and research collaborations. Long also co-organized several social and academic events within Wageningen including a writing week, a team-outing with his colleagues, and a presentation session under the SENSE graduate school's symposium. In the coming years, Long will continue working at his current research group as a postdoc researcher in the NWO/WOTRO Waterapps project on climate and water information services for sustainable food production in urbanizing deltas.

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SENSE PhD Courses

- Applied statistics (2013)
- Environmental research in context (2013)
- SENSE summer academy: Voice and presentation training and Debating training (2014)
- Research in context activity: 'Organising and convening the Environmental Change session for the 2nd Wageningen PhD Symposium' (2015)

Other PhD and Advanced MSc Courses

- The choice, Wageningen University (2015)
- Scientific writing, Wageningen University (2016)
- Pitch perfect, Wageningen University (2016)
- Career perspectives, Wageningen University (2016)
- Mobilising your - scientific - network, Wageningen University (2016)
- Career assessment, Wageningen University (2016)

External training at a foreign research institute

- Soil and Water Assessment Tool (SWAT) hydrological model training, Toulouse, France (2013)
- VMod hydrological model training, Aalto University and Environmental Impact Assessment (EIA) Centre of Finland, Espoo, Finland (2014)
- Research collaboration, Southern Institute of Water Resources Planning, Ho Chi Minh City, Vietnam (2015)

Management and Didactic Skills Training

- Supervising three MSc students with their MSc thesis (2014-2016)
- Assisting practicals of the MSc course 'Introduction to global change' and the MSc course 'Climate change adaptation in water management' (2015-2016)
- Guest lectures in the courses 'Disaster-proof planning and preparedness in water management' and 'Climate change adaptation in water management' (2015-2016)
- Organising the weekly PhD update meeting for the Water Systems and Global Change group (2013-2015)
- Co-organising the ESS-CALM group writing week (2014)

Oral Presentations

- *Extreme floods in the Mekong River delta under climate change: Combined impacts of upstream hydrological changes and sea level rise.* European Geosciences Union (EGU) General Assembly, 17-22 April 2016, Vienna, Austria
- *Mekong River flows and extreme floods under climate change.* International conference on Climate Change Impact and Adaptation in Southeast Asia's large river basins, 29-30 April 2015, Bogor, Indonesia

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