Deliang Chen
Junguo Liu
Qiuhong Tang *Editors*

Water Resources in the Lancang-Mekong River Basin: Impact of Climate Change and Human Interventions

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Chapter 1
Introduction

Deliang Chen, Junguo Liu, and Qiuhong Tang

1.1 The Region

The Lancang-Mekong River Basin (LMRB) is one of the most important transboundary river basins in the world, with a river length of 4,880 km and a total area of 795,000 km^2 (Fig. 1.1a) (Liu et al., 2022). The Lancang-Mekong River (LMR) originates from the Tibetan Plateau in the Qinghai Province in China. It flows from north to south through the Yunnan Province and the Tibet Autonomous Region, and is called the Lancang River within China. After entering the lower portion, the river is known as the Mekong River, and finally enters into the South China Sea. The Lancang-Mekong River is the 10th largest river in the world with an annual streamflow at the river mouth in the Mekong Delta of about 475 km^3/a (Liu et al., 2022). The upper Lancang River Basin accounts for 21% of the total basin area, and water supply here mainly comes from rainfall and snowmelt. The lower Mekong River Basin is shared by Laos (accounting for 25% of the total basin area), Thailand (23%), Cambodia (20%), Vietnam (8%) and Myanmar (3%), while streamflow in the lower basin comes mainly from precipitation and upstream flow. On average, the

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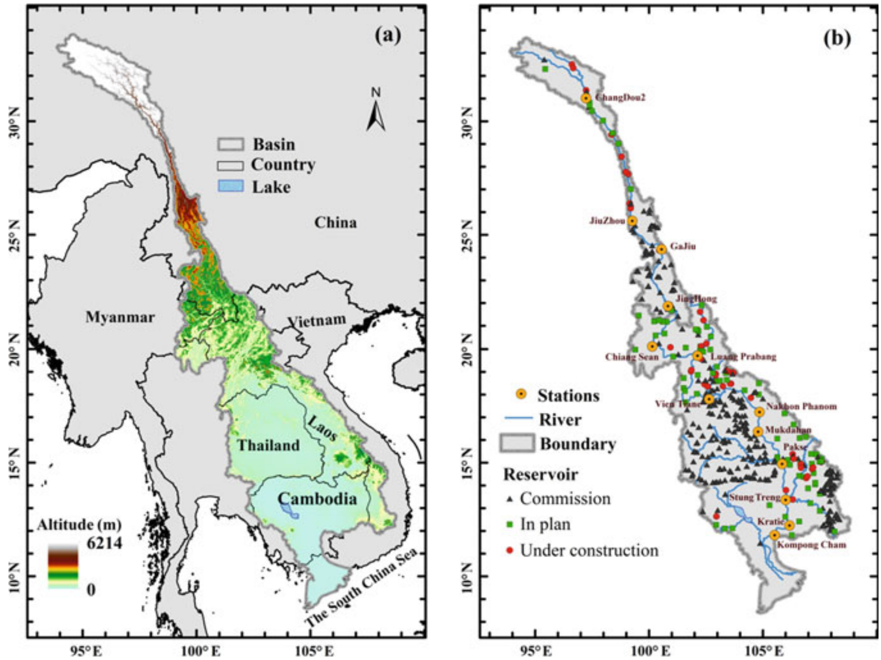

Fig. 1.1 **a** The Lancang-Mekong River Basin (LMRB). **b** The dams and major streamflow gauging stations in LMRB

countries' share of water flows in the basin is: China, 16%; Myanmar, less than 2%; Laos, 35%; Thailand, 18%; Cambodia, 18%; and Vietnam, 11%.

Located in the monsoon climate zone, the basin is affected alternately by the southwest monsoon and the northeast monsoon, resulting in the uneven precipitation distribution in time and space, and great volatility in the seasonal streamflow. The wet season (from June to November) is mainly controlled by the southwest monsoon rich in water vapour, and more than 80% of the precipitation is concentrated in this season. The dry season (from December to May) is mainly affected by the northeast monsoon, and from December to February is the cool season and from March to May is the hot season. In general, 75% of the total annual streamflow of the basin flows through the lower Mekong Delta from July to October, and affects the ecosystem and human activities in the downstream area with the rhythmic floods. The alternation of dry and wet seasons leads to seasonal reversal of streamflow in the lower Mekong basin: the river flows back into the Tonle Sap Lake (the largest lake in Southeast Asia) to be stored in wet seasons, while the Tonle Sap supplies the Mekong River in dry seasons. This is one of the most unique hydrological processes in the world (Wang et al., 2021).

The LMRB has complex natural conditions: the elevation difference in this basin is more than 5060 m from the river source in the Tibetan Plateau to the Mekong River estuary, with an average slope of 1.04‰. The northern part of the Lancang

River Basin is an alpine valley with average altitude of 3,500–5,000 m; and the southern part is a wide valley with an altitude between 1,000 and 3,500 m. As for the upstream of the Mekong River Basin, Myanmar and the northern part of Laos have a large area of mountains. The terrain of midstream in Thailand and Laos is a transition region from mountain to plain. The downstream located in Cambodia and southern Vietnam is mostly plains. In addition, the downstream Mekong Delta has a large area of floodplains, including the central floodplain from Kratie town to the border of Vietnam, the Tonle Sap floodplain with the Tonle Sap Lake and surrounding tributaries, and the Vietnamese Mekong Delta floodplains.

Over 70 million people live in the LMRB. Since the Angkor period (approximately the ninth to fifteenth centuries) or even earlier times, the LMRB has fed a large population with abundant water resources. Until now, riparian countries still highly rely on this commonly shared river.

After the agricultural reforms in the late 1980s, Vietnam has become one of the largest rice exporters in the world, with 90% of the rice exported from the Mekong Delta. The rural economy based on rain-fed agriculture provides 65% of the economic income of the Mekong River Basin. At the same time, the LMRB is one of the most biologically diverse basins in the world, second only to the Amazon. Rich species diversity in the LMRB has created the world's largest inland freshwater fishery, which provides a vital, and often only, source of animal protein for people in this basin. The residents in the lower Mekong River Basin depend on fish and other aquatic animals for 47–80% of their required protein intake, more than any other major basins in the world (Hecht et al., 2019; Hortle, 2007). The Tonle Sap Lake produces 60% of Cambodia's fish catches and solves the survival problem of nearly 10 million people (Burbano et al., 2020).

With the rapid urbanization and the population explosion, water resource conflicts in the LMRB are increasing. At the same time, the uneven distribution of precipitation has also exacerbated the problem of water disputes. All in all, the two important issues facing the LMRB are how to tackle increasing extreme events under climate change and how to manage water under increasing pressure from rapidly growing demands. The lower part of the basin is mainly located in the plains and deltas with flat terrain, which is vulnerable to flood disasters. Meanwhile, the increasing drought incidents also threaten the water security of the basin. According to the Emergency Events Database (EM-DAT, https://www.emdat.be/), the LMRB has recorded 173 floods and 23 droughts between 1990 and 2016, affecting 148.5 million people and causing a total of 61.4 billion US dollars of economic losses.

In order to tackle the increasing frequency and intensity of extreme events and meet the increasing energy demands in the LMRB, a large number of reservoirs have been constructed in the past decades. Before 2008, the basin was one of the least affected major river basins by human activity in the world with the effective reservoir capacity accounting for only 2% of the annual streamflow. By the end of 2021, the total storage capacity of the 103 reservoirs under operation in the basin had reached a staggering number of 100.3 km^3, accounting for 23% of the annual streamflow (Fig. 1.1b, according to GMDD, the Greater Mekong Dam Database, https://wle-mekong.cgiar.org/maps/). Among these dams, 23 are located in China, producing

18,081 MW of electricity annually, while 80 dams are located downstream generating 15,034 MW of electricity annually (Hecht et al., 2019). These reservoirs have brought huge social and economic benefits to the countries in the basin, including mitigating extreme events, increasing energy supply, improving river navigation conditions, and ensuring agricultural irrigation (Yun et al., 2021). On the other hand, reservoir expansion has also aroused many criticisms. For example, reservoir operation changes the streamflow and affects the flood characteristics in the river, which might affect the aquatic ecosystem and vegetation distribution (Yang et al., 2019). Further, decline in river network connectivity due to dams may hinder the migration and reproduction of fish and lead to a decline in food security (Anh et al., 2018). Also, the interception of sediment by the reservoirs may reduce the supply of soil nutrients and increase the erosion of the Mekong Delta (Schmitt et al., 2019).

1.2 Background and Context

The complex climate in the LMRB is of high spatiotemporal variability, shifting from plateau climate at the upper basin to temperate monsoon and tropical monsoon climates in the middle and lower basin. Tropical cyclones mainly influence the basin during the wet seasons, and it can partly cause the second peak of seasonal streamflow in September–November (Chen et al., 2019). The incursion of tropical cyclones into the LMRB is a major factor in the development of regional flood events (MRC, 2015). Tropical cyclones also play a vital role in mobilizing sediment of the Mekong River (Darby et al., 2016), where the river delta is threatened by land subsidence (~1.6 cm yr^{-1}) and sea level rise (Erban et al., 2014).

Over 80% of the people live close to the river, making the lower basin one of the world's largest inland fisheries (Ziv et al., 2012). There is increasing vulnerability of riparian countries to floods, which tends to cause fatalities and property damage, especially for those who live on the margins of economic development (MRC, 2015).

Under future climate change conditions, more frequent precipitation brought by the intensifying water cycle will greatly change the streamflow. Meanwhile, large-scale hydropower development would also profoundly change the way people live in this basin. In order to adapt to the changing environment and requirements of the society, a number of questions have been raised in recent decades which need to be dealt with properly. The important concerns include (1) trends of regional climate change in the past and future, (2) water resources change in terms of quantity and quality, (3) water usages for various sectors and their linkage to food and energy security, (4) impacts of climate change and dam construction on water-related hazards, (5) transboundary river management and governance. To address these concerns, it is necessary to comprehensively assess the combined impacts of climate change and human interventions on water resources in the LMRB.

1.3 Motivation and Framing of the Assessment

The LMRB is extremely sensitive to climate change. The warming rate here is higher than the mean global warming rate (Liu et al., 2022). Despite rich water resources (~8,000 m^3/cap/yr), the high temporal and spatial variabilities in runoff create frequent seasonal droughts. In the past few decades, the hydrological system within the LMRB has been significantly influenced by climate change, consequently exacerbating extreme events, e.g., droughts and floods. The climate change and human intervention induced impacts on water have been projected to be intensified in the near future, bringing unprecedented threats to human societies and ecosystems. To this point, we proposed this report entitled "*Water resources assessment in the Lancang-Mekong River Basin: Impact of climate change and human interventions*" to support socio-economic development through sustainable use of water by providing accurate and updated information on climate and water resource changes presented in a consistent way. It provides implications to support decisions and stakeholders at all levels.

This report provides a comprehensive, up-to-date picture of the current state of knowledge based on published articles and recent research from the author team. New evidence of past, present and projected future changes in climate and water resources is based on many independent scientific analyses from observations and simulations using models.

The report is an assessment similar to the Intergovernmental Panel on Climate Change (IPCC) assessment report. It is not a review or a textbook of climate and water sciences, but is based on the published scientific and technical literature available. Underlying all aspects of the report is a strong commitment to assessing the science comprehensively, without bias and in a way that is relevant to policy but not policy prescriptive.

1.4 Approach and Processes

Like many other environmental issues, climate change and water resources are complex, which poses a challenge to provide authoritative scientific evidence for policy makers to take actions. Over the past decades, it became clear that scientific assessment is a powerful tool to meet this challenge. It is particularly useful in reaching a consensus among a group of experts when there are diverse and sometimes contradictory evidences from a variety of indicators and perspectives, which can be demonstrated by the success of IPCC assessment reports.

This assessment followed the essential principles used in the above-mentioned global assessments. Specifically, we tried to involve experts who are active researchers and come from different countries as authors and review editors. Further, this assessment focuses on summarizing and evaluating the existing literature published in peer-reviewed journals, although occasionally official governmental documents and reports from regional and international organizations were also mentioned.

The assessment was designed and edited by Deliang Chen, Junguo Liu and Qiuhong Tang, and managed by Yuehan Dou and Kai Wang. A group of lead authors was appointed to lead each theme (chapter), and to invite and engage contributing authors to contribute to specific aspects of the assessment. When an expert on a specific topic was missing during the assessment process, an additional expert was invited to act also as contributing author. An important step in the process is the multiple reviews of the assessment. While the lead authors constantly reviewed the writings of the lead authors and contributing authors for their chapters, the editors commented on the drafts in several phases of the project. Finally, the complete chapter drafts were reviewed by review editors. The whole process took three years to complete.

1.5 Structure of the Report

This report consists of a short introduction and 8 thematic chapters covering climate change, surface water change, arsenic pollution, water utilization, water-food-energy nexus, water related hazards, water management, and water governance. In order to facilitate the accessibility of the findings of this report for a wide readership and to enhance their usability for stakeholders and users, each thematic chapter has an executive summary (abstract) highlighting major findings within the chapter. These executive summaries (abstracts) can be particularly useful for local government and stakeholders for water management towards sustainability.

Introduction (This Chapter): This chapter provides basic information on climate and water in the region, and introduces the framing, scope, process, and structure of the assessment.

Climate variability and climate change: Past and future (Chap. 2): This chapter assesses climate change in the past decades and projects future changes until the end of this century by using observed records and model simulations.

Surface water (Chap. 3): This chapter analyzes river network geometric features, assesses past and future changes in runoff, baseflow, and discharge, reveals the dynamics of the inundation area and turbidity in the Tonle Sap Lake.

Arsenic in Hydro-Geo-Biospheres of the Mekong River Delta: Implications for human health (Chap. 4): This chapter investigates arsenic cycling in Hydro-Geo-Biospheres in the Mekong River Delta and assesses the environmental impacts of groundwater arsenic as well as its health effects and exposure from drinking water and food. It also provides policy recommendations for arsenic mitigation.

Water utilization and the link to food and energy (Chaps. 5 and 6): These 2 chapters assess the water demand and utilization in the basin. It covers the relevant aspects from irrigation, hydropower generation, domestic water uses within the water-food-energy nexus.

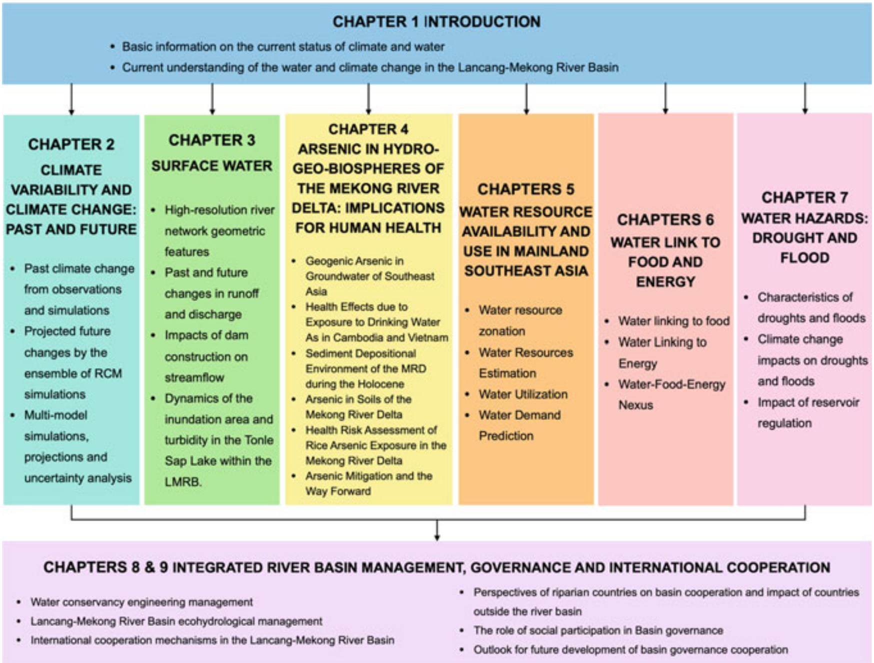

Fig. 1.2 The structure and contents of the chapters

Water hazards: drought and flood (Chap. 7): This chapter describes the characteristics of water related hazards including drought and flood in the basin. The impacts of climate change and human interventions on flood and drought are assessed to support the local risk mitigation and adaptation.

River basin management and governance (Chaps. 8 and 9): These chapters summarise the tradeoff between economic development and resource conservation in the basin, and present the major challenges for water resources management and governance. It also highlights the importance of international cooperation for transboundary water management.

A graphic presentation of the structure and contents of all chapters is provided in Fig. 1.2.

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Chapter 2
Climate Variability and Climate Change: Past and Future

Xuejie Gao, Qingyun Duan, Tinghai Ou, Yuanhai Fu, Xuewei Fan, Zhu Liu, Chiyuan Miao, and Chenwei Shen

Abstract The LMRB (LMRB) has experienced significant climate change, particularly over the last 50 years. An increase in the annual precipitation but with significant seasonal differences in the changes, and a remarkable warming are observed over the Basin. The region also experienced more frequent extreme events, such as an increase in extreme precipitation, as well as hot days and warm nights, a decrease in cold days and cold nights, and a more frequent occurrence of droughts. The future climate over

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the Basin is projected to be continuous warming, which is most significant by the end of the twenty-first century. A general wetting is projected over the region with the spatial pattern of the projected annual total precipitation change show consistencies with the present day condition. Differences are found between the global and regional climate model projections in the precipitation, indicating the uncertainties existing in the projections, and also the importance of the model resolution in projecting future climate.

2.1 Introduction

The region encompassing the Lancang-Mekong River has a plateau climate in its source region, but a typical monsoonal climate in most of the basin, with the monsoons often accompanied by the extreme events of heatwaves, droughts and floods, and tropical cyclones, (e.g. Chang et al., 2012; Ding & Chan, 2005; Tang-gang et al., 2007). Many studies have shown that significant climate change has been observed over the region during the last century, particularly over the last 50 years. Since the middle of the twentieth century, the average surface temperature and heat wave frequency have increased for the region. During 1952–2015, the annual precipitation trend was 0.5 mm/10 yr. However, there exists a significant difference between the dry and wet season. On the basin scale, a significant ($p < 0.05$) trend of wetting by 3.4 mm/10 yr was found in the dry season during water years 1952–2015, whereas in the wet season, there was a drying trend of −3.0 mm/10 yr (Irannezhad et al., 2020). The temperature in the LMRB has risen at a rate of 0.76 °C/10 yr during 1980–2010 (Fan & He, 2015). Extreme temperature events show also an upward trend (Thirumalai et al., 2017) with an increase in hot days and warm nights, and a decrease in cold days and cold nights (Ma et al., 2013).

Observations and model-based analysis form an important basis for gaining a scientific understanding of the climate variability and change that have occurred in the past, what are occurring right now, and what are going to happen in the future. Unfortunately, this region has a relatively sparse climate observational network. In climate studies, global datasets like the Global Precipitation Climatology Centre (GPCC) data (Adler et al., 2017) and gridded precipitation and other meteorological variables developed by the Climate Research Unit (CRU) of the University of Anglia (Harris et al., 2013) have often been used to investigate the observed climate change in the LMRB (Fan & He, 2015; Irannezhad et al., 2020). The dataset of Asian Precipitation-Highly Resolved Observational Data Integration Toward Evaluation of water resources (APHRODITE), generated by the Research Institute for Humanity and Nature and the Meteorological Research Institute of the Japan Meteorological Agency, is a long term regional daily-scale gridded precipitation dataset, generated by utilizing a dense network of in situ gauge records in Asia and, therefore, is better suited for climate studies in the LMRB (Irannezhad et al., 2020; Yatagai et al., 2009).

It is necessary to resort to climate models to gain insights into future climate change. As the primary tools in climate change studies, global climate models

(GCMs) have been widely used to simulate and project climate change at the global scale. The Intergovernmental Panel on Climate Change (IPCC) gathers and evaluates GCMs as part of the international climate change Assessment Reports (AR). IPCC has so far published six Assessment Reports (ARs). In each AR, the IPCC relies on the outputs of the GCMs participating in the Climate Model Intercomparison Projects (CMIPs). Archives of GCM outputs from different CMIPs offer opportunities to assess the climate model performance in simulating past climate and to analyse the projections for 21st-century climate change under different emission scenarios, and the potential effects of the changes at either global or regional scales (Bannister et al., 2017; Su et al., 2013).

The current phase of CMIP is the sixth (CMIP6). The GCMs in CMIP6 have significant improvements in the physical parameterisations (e.g. in representing the clouds), spatial resolution, and inclusion of additional Earth system components (e.g. ice sheets) and processes (e.g. the nutrient limitations in terrestrial carbon cycle), compared to those of the previous CMIPs (Eyring et al., 2016, 2019). In CMIP6, a new conceptual framework had been developed. It uses a diverse range of socio-economic and technological development scenarios, i.e. the Shared Socioeconomic Pathways (SSPs). SSPs are distinguished on the basis of anticipated challenges to adaptation and mitigation, which is different from the emissions pathways concluded in the IPCC Special Report on Emissions Pathways/Scenarios (Moss et al., 2010; O'Neill et al., 2016). The two main axes of the scenario matrix architecture are firstly, the future climate radiative forcing level which is characterized by the Representative Concentration Pathways (RCPs), and secondly, a set of alternative plausible trajectories for future global development (the SSPs) (Kriegler et al., 2014). The SSPs are based on five narratives describing the alternative pathways of socioeconomic development, including SSP1 for sustainable development, SSP2 for middle-of-the-road development, SSP3 for regional rivalry, SSP4 for inequality, and SSP5 for fossil-fueled development (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017). This new generation of pathways/ scenarios will facilitate the understanding of plausible socioeconomic and climate futures for the society.

While GCMs have contributed greatly to our understanding of climate variability and climate change at the global scale, they generally have rough spatial resolution and cannot capture the spatial climate change features at regional scales. To understand climate change at regional and local scales, one can use high-resolution regional climate models (RCMs), which are the limited area climate models forced by specified lateral conditions from GCMs or reanalysis. RCMs simulate atmospheric and land surface conditions, including Greenhouse Gas (GHG) and aerosol forcings. RCMs apply a dynamic downscaling approach to fill the gap between the coarse estimates of GCMs, which have practical requirements in the regional and locale scale impact studies, e.g. the finer spatial distribution of precipitation needed in hydrologic operations over small basins under global warming. RCMs have provided data for the impact studies and policymakers since the last three decades, and helped to increase knowledge of the present-day climate and future changes at regional levels, thus making them an important tool for investigating climate change in the LMRB (Tapiador et al., 2020).

This chapter describes the space–time features of climate variability and climate change over the LMRB based on climate observations and the GCM outputs from CMIP6 and the RCM outputs that are driven by GCMs from CMIP5. It is organized as follows. In Sect. 2.2, the climate change that has occurred in the LMRB over the last century is examined based on climate observations. Section 2.3 presents the simulations of the past climate and projections of future climate changes based on simulation and projection results from RCMs. In Sect. 2.4, a multi-model analysis of climate change in the LMRB is presented using the latest GCM outputs from CMIP6.

2.2 Past Climate Change from Observations and Simulations

There are a few rain gauges and stations with both temperature and precipitation records available over the LMRB (e.g., Wang et al., 2016). The data quality, in terms of continuity, is also quite low. Only very few stations have high quality data covering the latest 20-year period of model historical simulation, i.e., 1995–2014. Most of the stations with high quality data are located above the LMRB. To analyse the long-term (1961–2015) spatial–temporal variation of temperature and precipitation over the whole LMRB, gridded data sets interpolated from station data have been used in this work. For this purpose, gridded near-surface air temperature (T2m) and daily precipitation from the APHRODITE (http://aphrodite.st.hirosaki-u.ac.jp/index.html) during 1961–2015 are adopted (Yasutomi et al., 2011; 2012). The horizontal resolution of the APHRODITE data sets is 0.25° × 0.25° (latitude × longitude). Annual mean T2m and total precipitation are calculated based on the daily data sets. The average during 1961–2015 and 1995–2014 is to be shown together with their difference to illustrate the climate change during the recent 20 years which has been used for model evaluation. Empirical Orthogonal Function (EOF) analysis is also performed to show the major spatial–temporal variation patterns over the LMRB during 1961–2015.

Four extreme indices are investigated to illustrate the changes in extremes over the LMRB (Table 2.1). The two precipitation extreme indices (Rx5day and CDD) are calculated based on the gridded daily precipitation and temperature from the APHRODITE. Since there are no maximum and minimum temperatures available in APHRODITE, the two temperature extreme indices (TXx and TNn) from HadEX 3.0.3 (Dunn et al., 2020) are adopted. The HadEX data, with horizontal resolution 1.25° × 1.875° (latitude × longitude), have been interpolated to the APHRODITE data grid covering the LMRB using the inverse distance weighting (power 2) interpolation method.

Table 2.1 Definitions of the extreme temperature indices used

Index	Definition	Units
Rx5day	Annual maximum consecutive 5-day precipitation	mm
CDD	Annual maximum length of dry spell: maximum number of consecutive days with RR < 1 mm	Days
TXx	Annual maximum value of daily maximum temperature	°C
TNn	Annual minimum value of daily minimum temperature	°C

2.2.1 Near-Surface Air Temperature Change and Variability

The spatial variations in the annual mean T2m are quite large over the LMRB. The annual mean T2m increases from the northern to the southern river Basin, with the annual mean T2m lower than 0 °C over the northernmost of the headwater region and close to 30.0 °C over the southern Mekong Delta (Fig. 2.1a).

The annual mean T2m has significantly increased since 1950 when averaged over the whole Basin (Liu & Wang, 2020), which is higher than the mean global warming rate (Liu et al., 2021). Except for the southern Tonle Sap region, there is an overall significant warming trend over the LMRB. (Fig. 2.1b). The spatial pattern of the annual mean T2m during the recent 20 years, i.e. during 1995–2014, is similar to that during 1961–2015 but with an overall warm anomaly (Fig. 2.1c). The anomaly pattern of 1995–2014 with reference to 1961–2015 is similar to the linear trend of the annual mean T2m during 1961–2015 (Fig. 2.1d).

There are also regional and seasonal differences in the warming trend over the LMRB. For example, the warming is obvious during May and August compared to other months when averaging the whole basin (Liu & Wang, 2020), while winter T2m rise does the largest contribution to the annual T2m increase over the upper Lancang River (Wang et al., 2020). There is also obvious inter-decadal variation in the annual mean T2m. Even though there has been a general warming during the

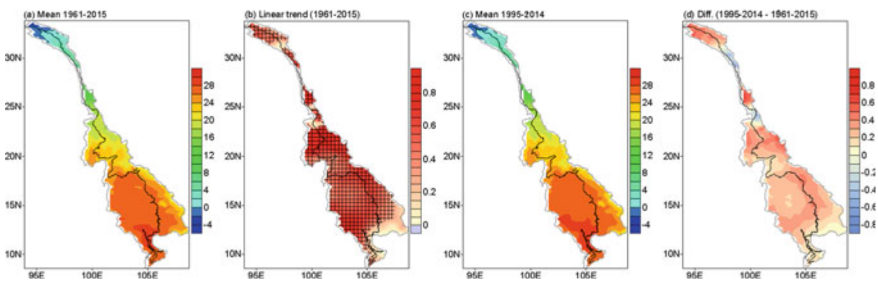

Fig. 2.1 Spatial distribution of **a** annual mean 2-m air temperature (T2m; °C) and its linear trend (°C/10 yr) during 1961–2015 (**b**), **c** annual mean T2m during 1995–2014 (°C), **d** the difference between mean T2m during 1995–2014 and 1961–2015 (°C) based on daily T2m from the APHRODITE (Yasutomi et al., 2011) (Areas with crosses show the region where the trend is significant at 0.05 level)

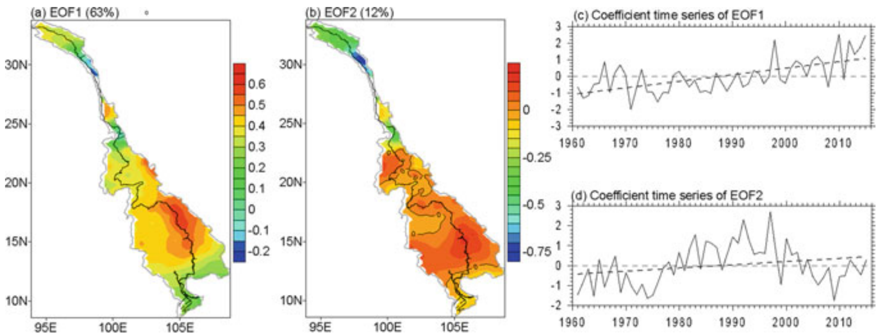

Fig. 2.2 Spatial distribution of **a** EOF1 and **b** EOF2 (°C) of annual mean T2m, and the coefficient time series of EOF1 (**c**) and EOF2 (**d**) during 1961–2015 based on daily T2m from the APHRODITE

past 60 years, there is a decrease in the annual T2m over some areas, especially over the middle and lower reaches of the Basin after 2008 (Liu & Wang, 2020). Wu et al. (2011) also show a decreasing trend in the annual T2m of Vientiane, Chaiyaphum, and Ho Chi Minh stations during 1980–2009, especially after around 2000.

The spatial variation in the warming trend is well illustrated in the first two EOF patterns, which explain 75% of the total variance of annual mean T2m (Fig. 2.2). Overall, there is a significant increase in the annual mean T2m over most of the Basin as shown in EOF1 and the related coefficient time series. There is also a change in the coefficient time series of EOF2 around 2000, centered over the middle and lower reaches of the Basin. This is related to the above-mentioned temperature decrease over these regions. The explained covariance of EOF1 is 63%, while it is only 12% for EOF2 (Fig. 2.2). The warming trend shown in Fig. 2.1b is largely explained by the EOF1 with a linear increase (Fig. 2.2c). Besides, there is a linear increase in the time series of EOF2 during the whole period which emphasize the warming covering a large part of the study area (Fig. 2.2d). Combining the first two EOFs, the warming is large over the middle to lower reaches of the river basin, with less warming over the southeast area.

In general, both GCMs and RCMs are more accurate in space than time (Huang et al., 2014; Sun et al., 2020), with a good ability to simulate the spatial distribution pattern of temperature. Models tend to underestimate the annual mean temperature in the upper and lower reaches of the Mekong River Basin, with a larger cold bias in the cold season than in the warm season (Ruan et al., 2019). Models can capture the warming characteristics in the basin, but the accuracy of the simulation is not good enough (Huang et al., 2014).

2.2.2 *Precipitation Change and Variability*

The climate of the LMRB belongs to the tropical monsoon (MRC, 2010). About 80–90% of the annual total precipitation falls from May to October (Costa-Cabral et al., 2008). The precipitation over the region is affected by Indian summer monsoon, East Asian summer monsoon, South Asian Summer Monsoon, as well as El Niño-Southern Oscillation (ENSO) (Dang et al., 2020; Fan & Luo, 2019; Hasson et al., 2013; Irannezhad et al., 2020; Räsänen & Kummu, 2013; Wang et al., 2022; Yang et al., 2019). Tropical Cyclones also have large effects on the total precipitation, especially in the southwest Basin (Chen et al., 2019), where GCMs have shown reliable skill in realistically simulating the track densities of Tropical Cyclones (Chen et al., 2020a, 2020b). On average, the northern headwater region is relatively dry with annual total precipitation of around 500 mm, while the southeastern region is relatively wet with annual total precipitation of more than 2000 mm (Fig. 2.3a).

Changes in annual precipitation are small during the period 1951–2017 when averaged over the whole Basin (Liu & Wang, 2020). A large spatial–temporal variation is obvious in the changes in precipitation. There is a decreasing trend in June and August and a small increasing trend in other months during 1951–2017 (Liu & Wang, 2020). Fan and He (2015) also show an increase in spring precipitation. Spatially, annual precipitation has slightly increased during 1960–2009 over the upper reach of the Mekong River, while a significantly decreasing trend has been found since 2000 (Wu et al., 2016). There are significant wetting and drying trends in annual total precipitation over the northeastern and most westerly parts of the Mekong River Basin during 1952–2015 (Irannezhad et al., 2020). A similar spatial pattern of the trend in annual precipitation can be found during 1961–2005 (Fig. 2.3b). In general, the rainy season precipitation contributes a large part to the annual total precipitation over the Basin (Chen et al., 2018). The spatial pattern of the interannual variability in the rainy season precipitation is highly correlated with the Indian monsoon and Western North Pacific monsoon co-variability (Yang et al., 2019). Asian monsoon circulation has weakened since the end of the 1970s due to the rapid warming in the Indian Ocean (Sooraj et al., 2015), which leads to a reduction of monsoon precipitation over the Basin. The less frequent tropical cyclones (Chen et al., 2019) may also

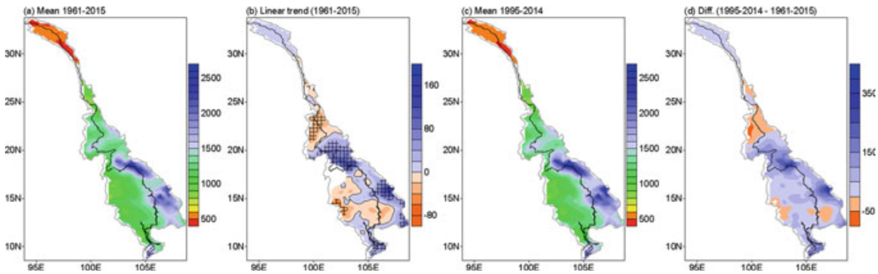

Fig. 2.3 Same as Fig. 2.1, but for annual total precipitation (Precip; mm) from the APHRODITE

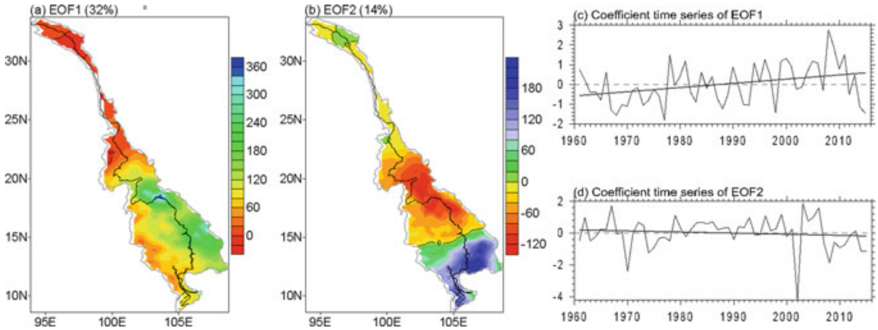

Fig. 2.4 Same as Fig. 2.2, but for annual total precipitation from the APHRODITE

lead to a decrease in wet-season precipitation over the region. The regional increase in precipitation can be attributed to the increase in extreme precipitations as shown by Li et al. (2022).

The spatial pattern of the annual precipitation during 1995–2014 is similar to that during 1961–2015 but with an overall wet difference (Fig. 2.3c). The difference pattern between 1995–2014 and 1961–2015 is similar to the linear trend of the annual precipitation during 1961–2015 (Fig. 2.3d).

The spatial–temporal variations of the annual precipitation over the River Basin can be clearly seen in the two EOF patterns and the related coefficient time series (Fig. 2.4). As can be seen in the first EOF pattern and the related coefficient time series, there is a general increase in the annual precipitation for the whole basin before 2009, while a decreasing trend is obvious afterwards. There is also a clear inter-annual dipole variation in the annual precipitation between the south and middle to the north Basin as can be seen from the second EOF pattern.

The observed spatial pattern and seasonal variation of the mean precipitation are well captured by GCMs (Ruan et al., 2018; Wang et al., 2017). A large part of GCMs evaluated have overestimated precipitation over the River Basin, especially during the monsoon season (Hasson et al., 2016; Ruan et al., 2018). Ruan et al. (2018) also pointed out that GCMs have a general failure in capturing observed trends in the wet season (53% of GCMs failed) and the dry season (65% of GCMs failed), as well as for annual total precipitation (44% of GCMs failed) over the lower Mekong Basin.

2.2.3 Variations and Changes in Weather and Climate Extreme Events

The LMRB is affected by increasing frequency both in extreme precipitation and drought, especially over the lower Mekong Basin (Liu et al., 2020; Tian et al., 2020). Extreme precipitation has generally decreased in the upper Mekong Basin but increased in the lower Mekong Basin during 1951–2015 (Irannezhad et al., 2021;

Liu et al., 2020). As can be seen from Fig. 2.5, the maximum extreme precipitation, maximum consecutive 5-day precipitation (Rx5day), is located over the east of the lower Mekong Basin. There are some regions with a significant increasing or decreasing trend in Rx5day over the lower or middle Mekong Basin respectively. The spatial pattern of mean Rx5day during 1961–2015 is similar to that of 1995–2014, with the anomaly pattern of 1995–2014 to 1961–2015 similar to the linear trend during 1961–2015. There is a general increase and decrease in the spatial–temporal variations of Rx5day over the upper/lower and middle Mekong Basin respectively as shown in Fig. 2.6.

There is a high agreement in the trend of drought frequency over the lower Mekong Basin. Adamson and Bird (2010) point out that Thailand, Cambodia, Laos, and Vietnam over the lower Mekong Basin, are vulnerable to increasing droughts. Guo et al. (2017) found an increasing trend in the frequency of drought over the north and south parts of the lower Mekong Basin during 1981–2016, with the Mekong Delta tending to have more long-term and extreme drought events. Lee and Dang (2019) also show that even though there is a decrease in the frequency of drought over the Mekong Delta during 1984–2015, there was a tendency to increase in the spatial distribution of drought with moderate and severe droughts over the region. Tian et al.

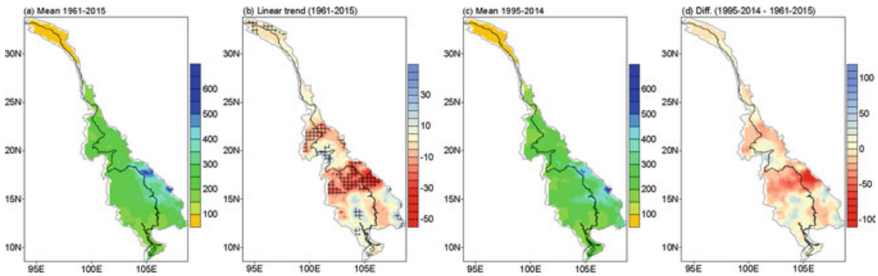

Fig. 2.5 Same as Fig. 2.1, but for Rx5day (mm) calculated based on daily precipitation from the APHRODITE

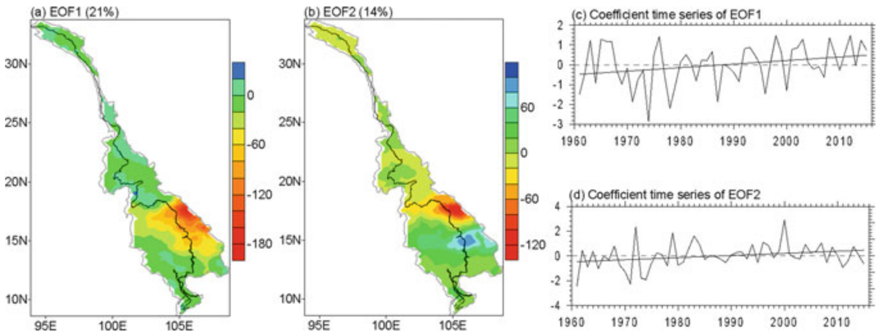

Fig. 2.6 Same as Fig. 2.2, but for Rx5day calculated based on daily precipitation from the APHRODITE

(2020) analyzed the temporal trend of drought over the LMRB during 1901–2019. They found that severe and exceptional droughts occurred more frequently during 1961–2019 compared to 1901–1960 with drought hotspots located in the middle and upper parts of the Lancang River Basin. About half of the lower reach of the LMRB has experienced an increase in severe and exceptional droughts, which are located principally in Thailand, east Cambodia, and part of Vietnam. The spatial distribution of mean and linear trend in the maximum length of dry spell: maximum number of consecutive days with RR < 1 mm (CDD) is shown in Fig. 2.7. There are two peak centres of CDD, one over the upper and the other over the center of the Mekong Basin. There is an increasing trend in CDD over the lower, middle and upper river basins. There is no significant trend in CDD during 1961–2015, but with clear inter-annual and inter-decadal variation in the CDD as shown by the EOF patterns (Fig. 2.8).

Changes in temperature extremes are shown by the maximum value of daily maximum temperature (TXx) and the minimum value of daily maximum temperature (TNn) (Figs. 2.9, 2.10, 2.11 and 2.12). Overall, there is an increase in both TXx and TNn, with the increases in TNn is robust than TXx. There is even a decrease in TXx over the southeast of the lower Mekong Basin.

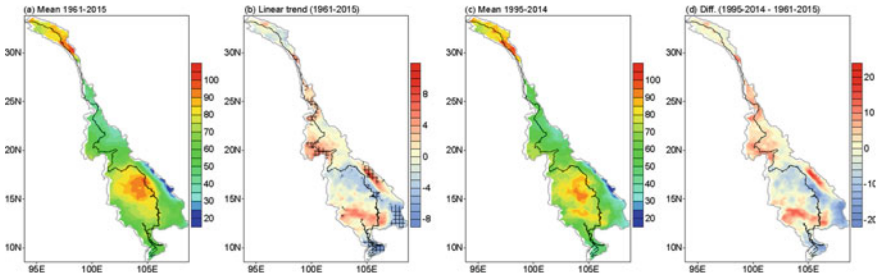

Fig. 2.7 Same as Fig. 2.1, but for CDD (days) calculated based on daily precipitation from the APHRODITE

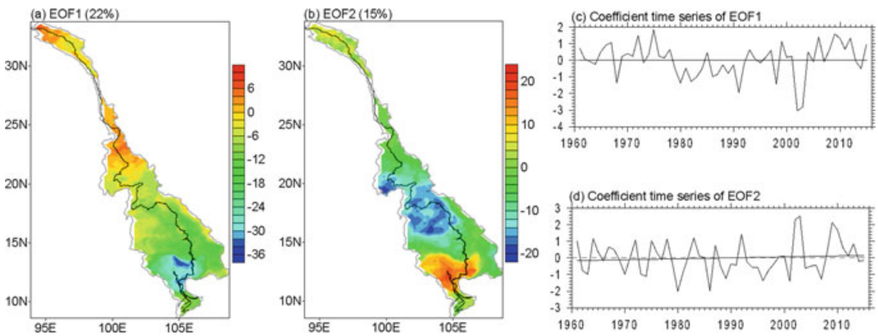

Fig. 2.8 Same as Fig. 2.2, but for CDD calculated based on daily precipitation from the APHRODITE

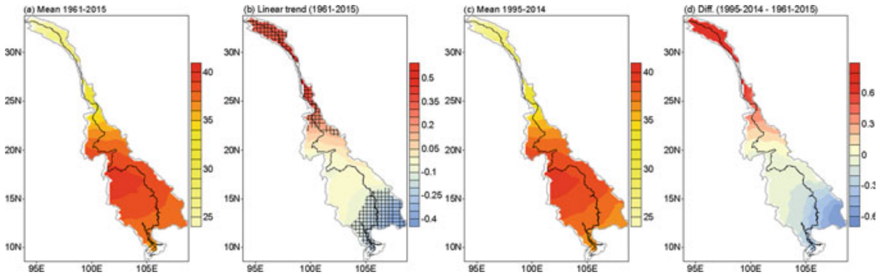

Fig. 2.9 Same as Fig. 2.1, but for TXx (°C) from gridded extremes indices, HadEX 3.0.3 (Dunn et al., 2020), which has been interpolated to the APHRODITE grid

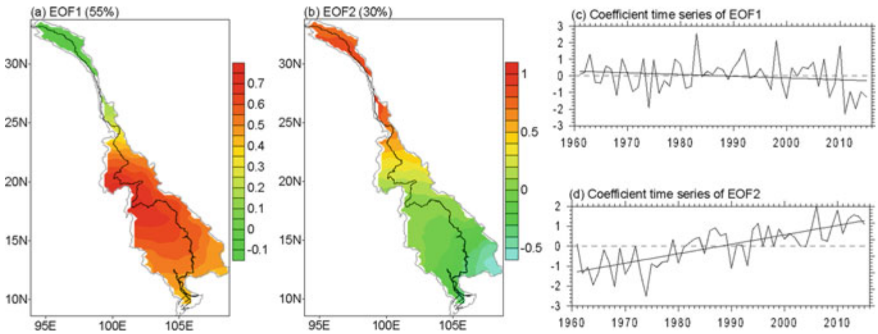

Fig. 2.10 Same as Fig. 2.2, but for TXx from HadEX 3.0.3 which has been interpolated to the APHRODITE grid

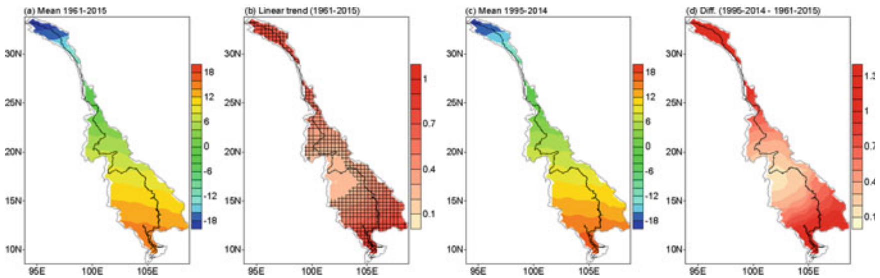

Fig. 2.11 Same as Fig. 2.9, but for TNn (°C) from HadEX 3.0.3 which has been interpolated to the APHRODITE grid

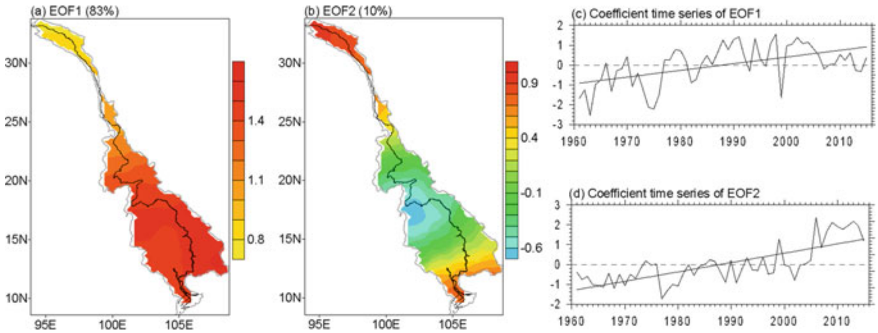

Fig. 2.12 Same as Fig. 2.11, but for TNn from HadEX 3.0.3 which has been interpolated to the APHRODITE grid

2.3 Projected Future Changes by the Ensemble of RCM Simulations

As shown in Sect. 2.2, the LMRB has experienced significant changes in climate in the last few decades. Understanding future climate change is crucial for the region to implement proper adaptation and mitigation measures. Application of high-resolution RCMs is particularly important over the Basin, which is characterized by unique weather/climate systems, complex coast lines and topography.

In this section, we report the projected climate change over the Basin based on an ensemble of twenty-first century projections with an RCM, the RegCM4 (Fu et al., 2021b). RegCM4 is developed and maintained by the Abdus Salam International Center for Theoretical Physics (Giorgi et al., 2012), and is one of the most widely used RCMs in the world.

RegCM4 was driven by five different CMIP5 GCMs and run over the CORDEX Phase II East Asia region, covering the whole of the Basin in the simulations. The GCMs are CSIRO-Mk3-6-0, EC-EARTH, HadGEM2-ES, MPI-ESM-MR, and NorESM1-M. The model is run at a grid-spacing of 25 km with the simulations covering 1971–2005, the historical period, using GHG concentrations, and 2006–2098, the future period under the RCP4.5 pathway (Gao et al., 2018). Here 1995–2014 is used as the reference period (present day), 2041–2060 and 2079–2098 as the mid- and end of the twenty-first century, respectively, following the periods used in the IPCC Sixth Assessment Report (IPCC AR6) (Lee et al., 2021).

The observation datasets of temperature and precipitation used to validate the present day simulations are the gridded observational dataset CN05.1 (Wu & Gao, 2013) over the Lancang River Basin, together with the APHRODITE (Yatagai et al., 2012) over the Mekong River Basin. The daily mean maximum and minimum temperatures employ also CN05.1 over the Lancang River Basin, but the Climate Prediction Center (CPC) Global Daily Temperature dataset (https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html) over the Mekong River Basin. The model outputs and the

CPC dataset are all bilinearly interpolated to the same grids of 0.25° (latitude) × 0.25° (longitude) as in CN05.1 and APHRODITE.

This section focuses on the ensemble mean of temperature and precipitation during the dry/cold season of November to March (NDJFM), the wet/warm season of May to September (MJJAS), and the whole year. Validation and inter-comparison of the models for both the present day period simulation and future changes between the driving GCMs and RegCM4 are provided. Two temperature extreme indices of TXx and TN, and two precipitation extreme indices of CDD and Rx5day are used to assess the simulation and projections in extremes by RegCM4.

2.3.1 Validation of the Present day Simulation

Surface air temperatures from the model simulations is compared against observations for the present day period of 1995–2014. Temperatures from the ensemble of the five GCM (ensG) and five RegCM4 (ensR) simulations along with observations in the dry and wet season, and the whole year, are shown in Fig. 2.13. In the observations (Fig. 2.13a–c), the lower reaches of the Basin is dominated by tropical climate, with prevailing temperatures warmer than 25.0 °C throughout the year. In the upper reaches in the north, both latitudinal and topographic dependences are found, with the lowest temperatures (<−10.0 °C) found during the dry season, and reaching >0 °C during the wet season. Regional mean temperatures in the dry and wet seasons, and the whole year are 19.9, 24.2, and 22.3 °C, respectively, over the Basin.

The broad pattern of the temperature from observation is reproduced in general by both ensG and ensR over the region of mainland Southeast Asia (MSEA), while ensR provides much finer spatial details, thus in better agreement with the observations (Fu et al., 2021b), although to a less extent in the River Basin (Fig. 2.13g–i). The temperature gradient due to the steep topography over MESA is realistically reproduced by ensR but not by ensG (Fu et al., 2021b). General cold biases prevail in both ensG and ensR during all seasons and the annual mean, greater in the dry than the wet season (not shown for brevity). Some small scattered warm biases are found along the eastern edge of the lower reach of the River Basin during the wet season and the whole year. Regional mean biases in the dry, wet seasons, and the whole year over the Basin are −2.9, −1.0, and −1.8 °C in ensG, and −2.7, −1.3, and −1.9 °C for ensR, respectively.

For precipitation, it is generally quite dry in the dry season over the Basin in observations, with less than 200 mm of precipitation over most places (Fig. 2.14a). With the monsoon dominating in the wet season, precipitation greater than 400 mm, with maxima reaching up to 1000 mm over the eastern part, is observed (Fig. 2.14b). The annual mean precipitation shows a similar pattern as the wet season but with larger values (Fig. 2.14c). The mean precipitation over the Basin in the dry season, the wet season, and the whole year are 118, 1018, and 1342 mm, respectively.

Similar to temperature, the general pattern, magnitude, and seasonal evolution of the observed precipitation are well reproduced over MSEA and LMRB by both

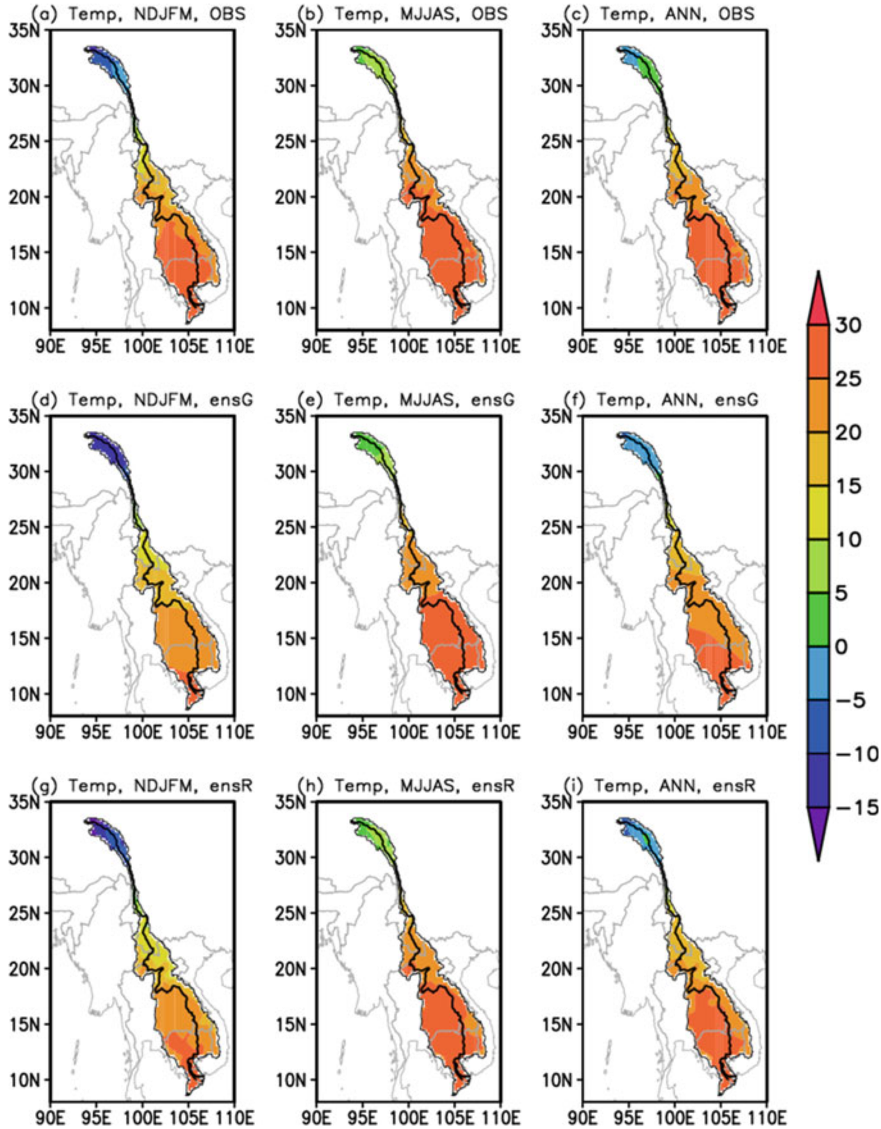

Fig. 2.13 Distribution of the present day (1995–2014) temperature over the LMRB. Observation in the dry season (**a**), the wet season (**b**), and the whole year (**c**); simulation by the ensemble of GCMs (ensG) in the dry season (**d**), the wet season (**e**), and the whole year (**f**); simulation by the ensemble of RegCM4 (ensR) in the dry season (**g**), the wet season (**h**), and the whole year (**i**). Unit: °C

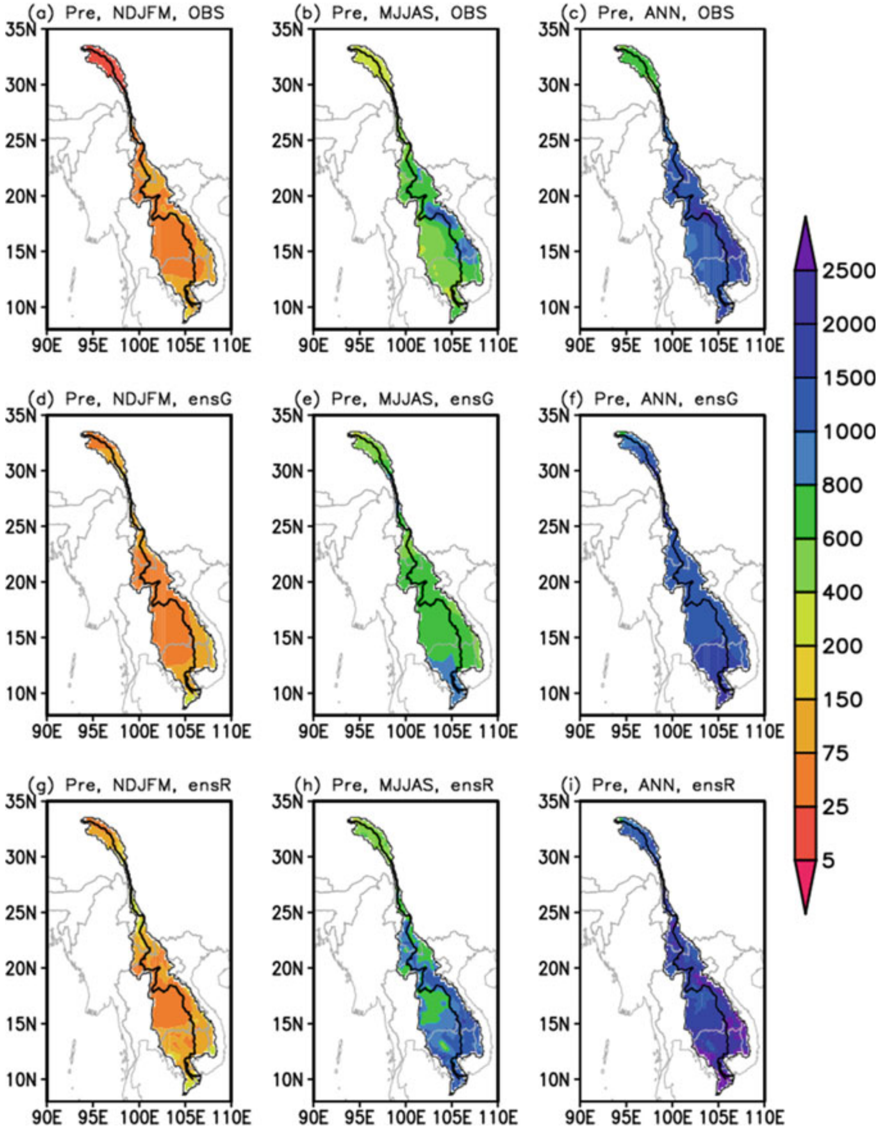

Fig. 2.14 Same as Fig. 2.13, but for precipitation. Unit: mm

ensG and ensR, while more regional details are provided by ensR compared to ensG (Fu et al., 2021b) (Fig. 2.14d–i). In addition, the ensR even exhibits finer spatial structure compared to the observation over the region, a result not surprising with the sparse distribution of observation sites there. A general overestimation is found for precipitation simulations in the model for both the dry and wet seasons, and the annual mean, more significant in ensR. Underestimation over places of the middle

Basin by both ensG and ensR in the dry season, and eastern part of the Basin by ensG in the wet season and the whole year, is found. Note that the "observational" precipitation may well underestimate the precipitation over the mountainous ranges due to the lack of observing sites in the high altitudes, and lack of the gauge undercatch corrections (Adam & Lettenmaier, 2003). Regional mean precipitation over the Basin in the dry and wet seasons, and the whole year, are 126, 1123, and 1432 mm for ensG, and 182, 1547, and 1982 mm for ensR, respectively.

The observated and the ensR simulated (ensG is not shown for brevity) extreme indices of TNn and TXx are presented in Fig. 2.15. For the TNn observation (Fig. 2.15a), the coldest temperatures are found over the head of the Basin (<−20 °C). Above zero temperatures are found in other places, and reach 15 °C in southern end of the Basin. The observed spatial pattern of TNn is well reproduced by ensR, although with general cold biases (Fig. 2.15b). The bias is the largest, >−9.0 °C, over the head regions, but this may be related to the sparse distribution of observing stations there. The bias is much smaller over the lower Basin (−3.0 °C). The regional mean values of TNn from the observation and ensR over the Basin are 7.6 and 3.3 °C, respectively.

The values of TXx (Fig. 2.15c, d) range from 20 to 30 °C over the upper and 30 to 35 °C over the lower Basin. Cold biases >5 °C exist over the head regions, and a mix of cold and warm biases within ±2 °C is found over other places. Regional mean values of TXx over the Basin for the observations and ensR are 35.5 and 34.5 °C, respectively.

The observed CDD shows the smallest values (30–40 d) along the eastern edge of the Basin (Fig. 2.16a). Values >50 d are located over the head regions, most of Cambodia, and eastern Thailand. The general CDD spatial pattern is reproduced well in ensR, but with prevailing underestimations (Fig. 2.16b), likely due to the too many days of drizzle as commonly found in climate models. The regional mean from observation is 46 d, while in ensR it is 30 d over the Basin.

The spatial distributions of Rx5day shows strong topographic dependences, with greater values >150 mm mostly along the mountain ranges over the border areas of Vietnam and Laos (Fig. 2.16c). The topographic effect is more pronounced in ensR, characterised by greater values, and more extended areas along the Truong Son Mountain (Fig. 2.16d). A general overestimation of Rx5day is simulated (figure not shown for brevity), consistently with the mean precipitation. The average over the Basin for ensR is 177 mm, greater than the 114 mm in the observations.

2.3.2 Future Changes

Figure 2.17 shows the projected temperature change over the Basin in the dry and wet seasons, and the whole year by the end of the twenty-first century. Substantial warming is found, more significant in the dry compared to the wet season and over the upper compared to the lower Basin. In the dry season, the warming in ensG is evenly distributed, with values >2.2 °C over most of the Basin (Fig. 2.17a), while in ensR,

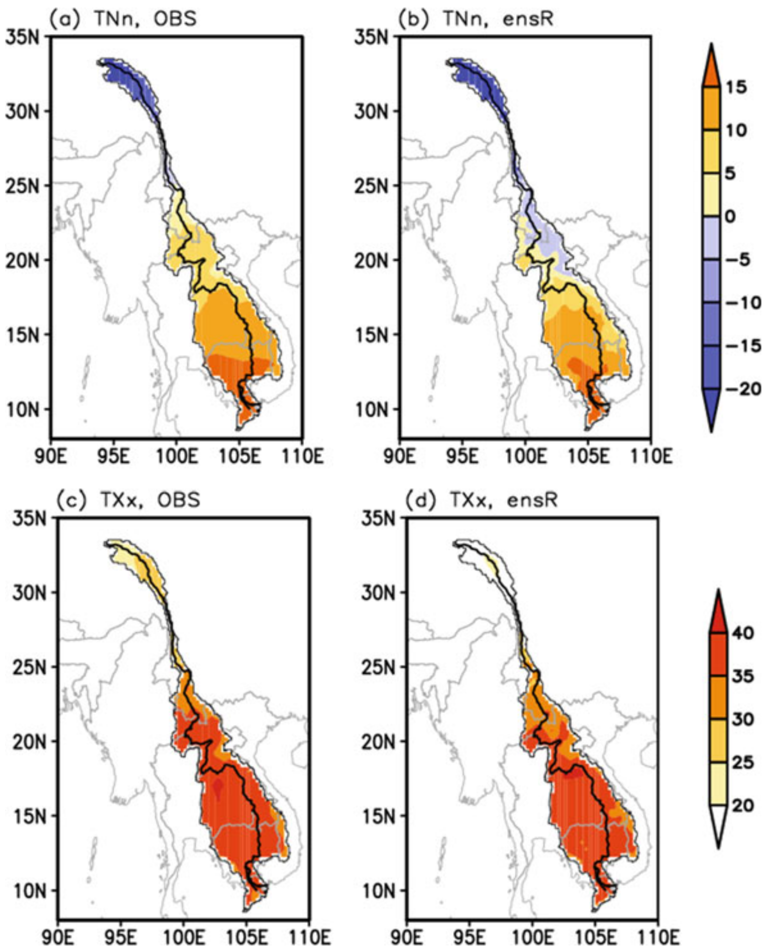

Fig. 2.15 Distribution of present day (1995–2014) TNn over the LMRB in observation (**a**) and simulated by ensR (**b**); **c**, **d** same as **a**, **b**, but for TXx. Unit: °C

large sub-regional variability is found, with >3.0 °C values over the source regions with high altitudes, and <2.0 °C values over the lower Basin (Fig. 2.17d). This effect of warming amplification with elevation has been found in previous studies, mostly due to the response to the reduction of snow cover (e.g. Giorgi et al., 1997; Fu et al., 2021a). The values of regional mean warming over the Basin for ensG and ensR are 2.3 °C (with inter-model spread of 1.4–3.6 °C) and 1.9 °C (0.7–2.7 °C), respectively (Table 2.2). Thus lower region-mean warming and inter-model spread are found in RegCM4, likely due to the same physics schemes used in all runs, which modulate the effect of lateral boundary forcings.

The warming is lower in the wet season (Fig. 2.17b, e) for both ensG and ensR. Again, lower warming is simulated in ensR in general compared to ensG. In ensG,

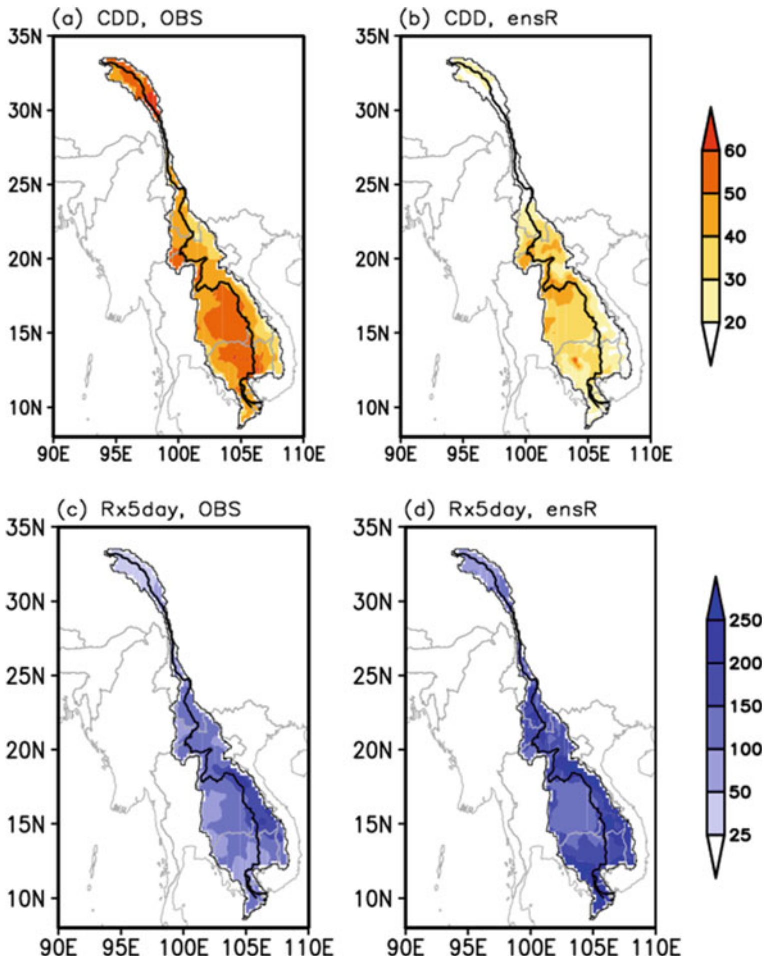

Fig. 2.16 Same as Fig. 2.15, but for CDD and Rx5day. Units are d for **a**, **b** and mm for **c**, **d**

the least warming values <1.6 °C is found over the lower Basin (Fig. 2.17b). The warming is greater over the mid- and upper-Basin, with values ranges from 2.0 to 2.4 °C. For ensR, lower than 1.6 °C warming are simulated over most of the Basin, except in the head regions (Fig. 2.17e). The regional mean warming over the Basin is 1.9 °C (1.4–2.5 °C) and 1.4 °C (1.0–2.2 °C) for ensG and ensR, respectively.

The projected annual mean temperature changes, either the magnitude or distribution, lie between the dry and wet seasons (Fig. 2.17c, f). In ensG, the warming ranges mostly from 2.1 to 2.4 °C over the whole Basin (Fig. 2.17c). In ensR, more pronounced warming in the north, with the largest values >2.4 °C, and lower in the south, in the range of 1.4–1.6 °C, are found (Fig. 2.17f). The projected mean

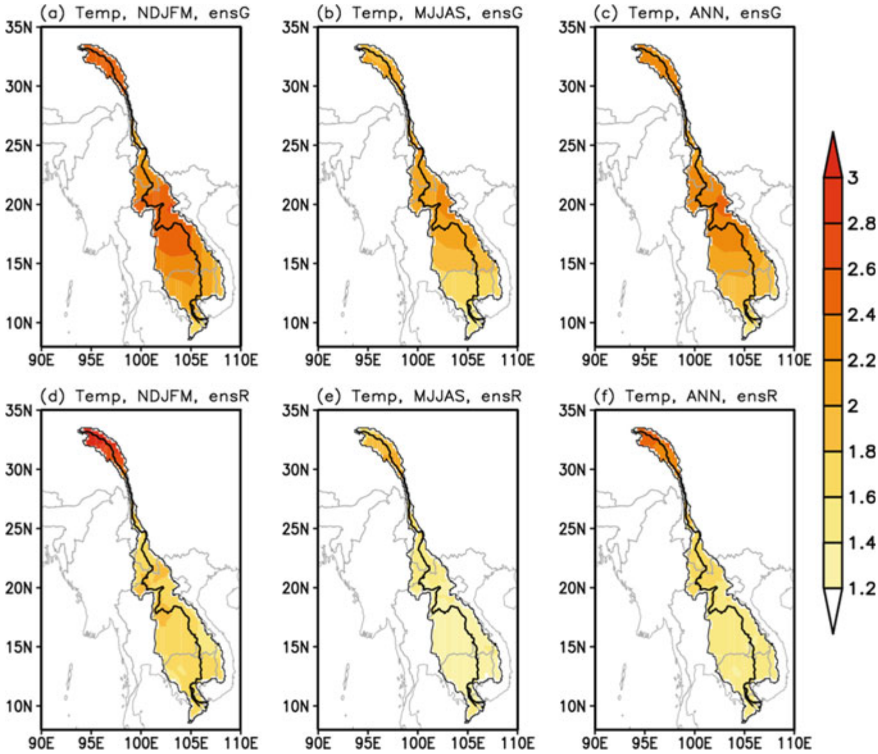

Fig. 2.17 The projected changes of temperature by the end of the twenty-first century (2079–2098) under RCP4.5 over the LMRB. By ensG in the dry (**a**) and wet (**b**) seasons, and the whole year (**c**); by ensR in the dry (**d**) and wet (**e**) seasons, and the whole year (**f**). The sign of the changes for the inter-models and cross simulations are in good agreements, thus not shown for brevity. Unit: °C

Table 2.2 Regional mean changes temperature and precipitation for the dry (NDJFM), wet (MJJAS) seasons, and the annual mean over LMRB projected by ensR and ensG under RCP4.5 in the mid- (2041–2060) and end (2079–2098) of the twenty-first century (relative to the present day of 1995–2014)

Variable		NDJFM (ensG/ensR)	MJJAS (ensG/ensR)	ANN (ensG/ensR)
Temperature (°C)	2041–2060	1.5/1.3 (0.9–2.3/0.7–1.7)	1.3/0.9 (1.1–1.6/0.5–1.5)	1.4/1.1 (1.1–1.9/0.9–1.6)
	2079–2098	2.3/1.9 (1.4–3.6/0.7–2.7)	1.9/1.4 (1.4–2.5/1.0–2.2)	2.1/1.6 (1.5–3.0/1.0–2.4)
Precipitation (%)	2041–2060	5/4 (−10–30/−3–12)	2/−2 (−2–7/−4–1)	3/1 (−2–7/−2–3)
	2079–2098	9/7 (−16–33/−3–15)	4/−2 (−4–9/−5–0)	6/1 (2–13/−2–4)

Note Values in the brackets are the minimum–maximum in the five GCMs/RegCM4 simulations changes of annual temperature for ensG and ensR are 2.1 °C (1.5–3.0 °C) and 1.6 °C (1.0–2.4 °C), respectively, over the Basin.

The regional averaged warming and the inter-model/cross simulation spreads of ensG and ensR during the mid- twenty-first century over the Basin are also presented in Table 2.2. The changes are in general consistent with the end of the century but to smaller values, and with greater warming during the dry season, and in ensG compared to ensR.

Figure 2.18 presents the precipitation changes at the end of the twenty-first century. For ensG during the dry season, a prevailing increase over the basin is found except in the southeastern corner (Fig. 2.18a). Values of the increase are mostly >15%, with maxima reaching over 20%. The inter-model agreement of the sign of change is high in the mid- and upper Basin, with greater increases there. The change of ensR shows consistencies, except for the finer spatial detail (Fig. 2.18d). Regional changes of precipitation for ensG and ensR are 9% (−16 to +33%) and 7% (−3 to +15%), respectively, over the Basin (Table 2.2).

During the wet season, general increases of precipitation in ensG, with the largest increase by >10% over the Mekong Delta are found (Fig. 2.18b), excerpt the slight

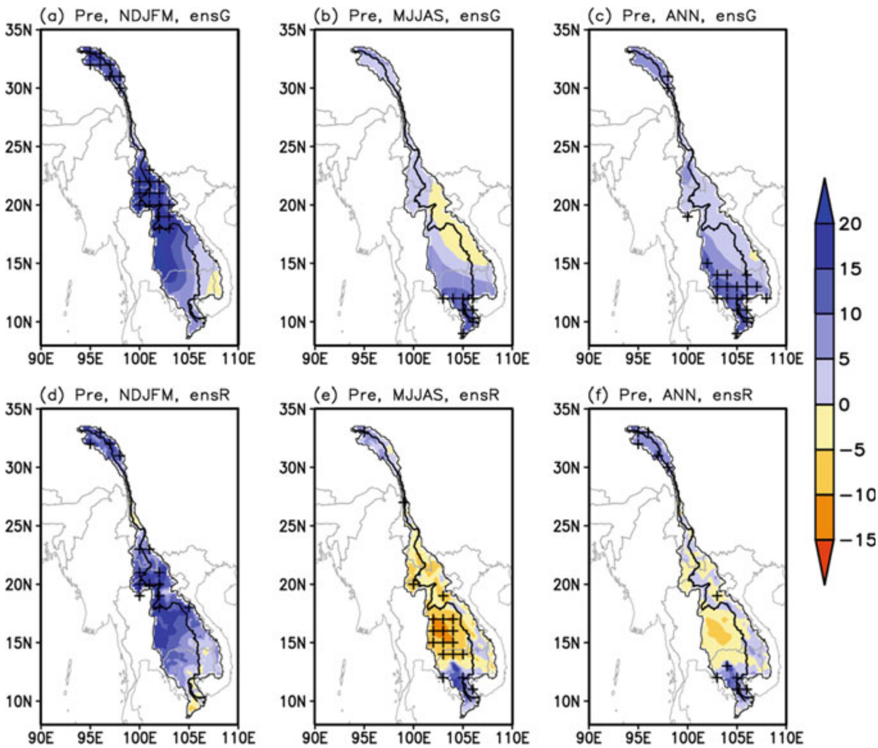

Fig. 2.18 Same as Fig. 2.17, but for precipitation. The cross indicates at least four out of the five GCMs/RegC4 simulations agree on the sign of change. Unit: %

decreases by <5% in eastern part of the Basin. The changes show low inter-model agreements in most places, except over the Mekong Delta with larger increases. Meanwhile, the projected precipitation exhibits a general decrease in ensR over almost all the places, with good agreement in the change sign over the places with larger changes (>−5%) (Fig. 2.18e). The largest decrease by 10–15% is mainly located in southeastern Thailand. The regional mean change is positive, by 4% (−4 to +9%) over the Basin in ensG, but negative by −2% (−5 to 0%) in ensR (Table 2.2). It is difficult to ascertain the cause of the difference, but previous studies have shown, that models with higher resolution tend to represent the dynamics of the East Asia monsoon better (Gao et al., 2006, 2012), and this may have an effect on the changes projected.

In general, the pattern of annual mean precipitation change is consistent with those in the wet season. For ensG, a general increase is found over the Basin, with the largest increase greater than >5%, and good inter-model agreements over the southwestern edge of the Basin (Fig. 2.18c). For ensR, a mix of positive/negative changes within ~ ±5% are found, with low coress-simulation agreements over almost all of the region (Fig. 2.18f). The regional mean changes in annual mean precipitation for ensG and ensR are 6% (+2 to +13%) and 1% (−2 to +4%), respectively, over the Basin (Table 2.2).

The projected regional mean precipitation changes over the Basin during the mid-twenty-first century are about half as large as by the end of the century for ensG, and during the dry season for ensR. Closer values for the changes in ensR between the mid- and end of the century during the wet season and the whole year (Table 2.2).

Figure 2.19a, b show the distributions of projections in the temperature extreme indices, TNn and TXx, at the end of the twenty-first century from ensR. The change of both TNn and TXx show significant increases under the warming, indicating fewer cold events and more frequent heat waves in the future. For TNn, the increases are greater over the high-latitude and high-altitude regions, with values of increase >3.0 °C (Fig. 2.19a). This is possibly caused by the reduction in snow cover and thus the snow albedo feedback effect. The increase tend to be much lower to the south, range from ~1.0 to 2.0 °C. The increases in TXx show inhomogeneously distributions (Fig. 2.19b), with values greater than 2.0 °C found over the upper and middle Basin, and less than 1.4 °C over the Mekong Delta in the south. Regional mean changes for TXx and TNn are 1.8 °C (0.9–2.6 °C) and 2.1 °C (1.7–2.9 °C), respectively, over the Basin (Table 2.3).

Changes in CDD and Rx5day by the end of the twenty-first century are shown in Fig. 2.19c, d, respectively. For CDD, a pronounced increase over a broad area in the middle and lower Basin, including northern Laos, eastern Thailand, and most of Cambodia, is found, with increases ranges from 2 to 4 days (10–25%) in correspondence with the generally decreased precipitation in the wet season and consequently the whole year (Fig. 2.18), although with low cross simulation agreements. Meanwhile, CDD is projected to decrease by 2–4 days over the upper Basin and the eastern part of middle Basin.

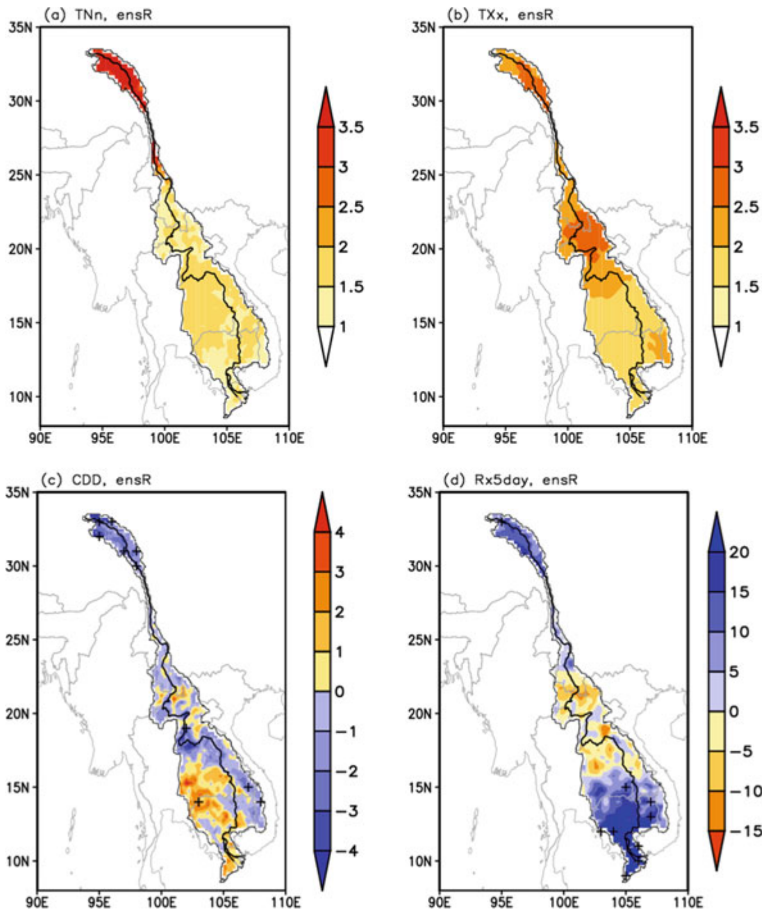

Fig. 2.19 The projected changes of TNn (**a**), TXx (**b**), CDD (**c**) and RX5day (**d**) by the end of the twenty-first century under RCP4.5 over the MRB in ensR. The cross indicates at least four out of five GCMs/RegCM4 simulations agree on the sign of change. Units are: °C, °C, day, and %, respectively

Table 2.3 Projected regional mean changes of TNn, TXx, CDD, and Rx5day over LMRB by ensR at the mid- (2041–2060) and end (2079–2098) of the twenty-first century under RCP4.5

Periods/variable	TNn (°C)	TXx (°C)	CDD (days)	Rx5day (%)
2041–2060	1.3 (1.1–1.8)	1.5 (1.1–2.0)	0.4 (−0.8–1.8)	5.6 (0.2–14.5)
2079–2098	1.8 (0.9–2.6)	2.1 (1.7–2.9)	−0.3 (−1.8–1.4)	8.4 (−1.1–16.8)

Note The values in brackets are the minimum–maximum in the five GCMs/RegCM4 simulations

The Rx5day is projected to increase by 10–25% over the upper and lower Basin, with the largest increase >50% found over the Mekong Delta with good cross simulation agreements (Fig. 2.19d). For the middle Basin, the change is a decrease by 5–15%. Comparison with change of CDD (Fig. 2.19c), both increases in CDD and Rx5day are found over lower Basin, suggesting the greater risk of the increase in both flood and drought disasters over the area in the future. Regional mean changes of CDD and Rx5day are −0.3 d (−1.8 to +1.4 d) and 8.4% (−1.1 to +16.8%), respectively, over the LMRB (Table 2.3).

2.4 Multi-model Simulations, Projections and Uncertainty Analysis

2.4.1 Evaluations of Historical Simulations

The spatial distributions of annual total precipitation and annual mean temperatures from the 16 CMIP6 models (Table 2.4) and APHRODITE observations over the LMRB are shown in Figs. 2.20 and 2.21. Generally, both the observed annual total precipitation and annual mean temperature exhibit an increasing gradient from the north to south of the Basin. Most CMIP6 models can reproduce the spatial distribution of annual temperature over the LMRB, despite there being slightly consistent cold biases for most models. The multi-model mean results are notably similar to observations in most regions, and the biases are relatively smaller than those of most individual models. In contrast, precipitations estimated by various CMIP6 models exhibit larger differences, and most models overestimate the precipitation compared with the APHRODITE observations. The BCC-CSM2-MR, CESM-WACCM, CESM2, CanESM5, GFDL-ESM4, UKESM1-0-LL models especially overestimate the annual total precipitation in the southern part of the LMRB. Similarly, CMIP6 model mean precipitation estimation behaves better than most individual models.

The agreement between model-simulated and observed precipitation and temperature was further evaluated through the Taylor diagrams, considering their spatial correlations, root-mean-square differences, and the amplitude of their variations (represented by their standard deviation). Figure 2.22 shows the precipitation and temperature Taylor diagram for the climatology of the period 1995–2014 for individual CMIP6 models and model mean over the LMRB. Based on the Taylor diagrams, most models show good performance for temperature, with a correlation coefficient typically >0.9 and a close match to the APHRODITE observations. Also, most of the models exhibit a ratio of the standard deviations that is close to 1, and the centred pattern RMSE difference range was 0.2–0.3. Comparatively, CAMS-CSM1-0, CESM2-WACCM, CESM2, and UKESM1-0-LL perform better over the LMRB. IPSL-CM6A-LR and FGOALS-g3 present relatively poor performance compared to

Table 2.4 List of 16 CMIP6 models in this study and their spatial resolution

Model name	Modeling center	Spatial resolution
BCC-CSM2-MR	Beijing Climate Center, China	320 × 160
CAMS-CSM1-0	Chinese Academy of Meteorological Sciences, China	320 × 160
CESM2-WACCM	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory, United States	288 × 192
e	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory, United States	288 × 192
CNRM-CM6-1	National Centre for Meteorological Research, France	256 × 128
CNRM-ESM2-1	National Centre for Meteorological Research, France	256 × 128
CanESM5	Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Canada	128 × 64
EC-Earth3-Veg	EC-Earth Consortium, Europe	512 × 256
EC-Earth3	EC-Earth Consortium, Europe	512 × 256
FGOALS-g3	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, China	180 × 80
GFDL-ESM4	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, United States	288 × 180
IPSL-CM6A-LR	Institut Pierre Simon Laplace, France	144 × 143
MIROC-ES2L	JAMSTEC (Japan Agency for Marine-Earth Science and Technology), AORI (Atmosphere and Ocean Research Institute, The University of Tokyo), NIES (National Institute for Environmental Studies) and R-CCS (RIKEN Center for Computational Science), Japan	128 × 64
MIROC6	JAMSTEC, AORI, NIES and R-CCS, Japan	256 × 128
MRI-ESM2-0	Meteorological Research Institute, Japan	320 × 160
UKESM1-0-LL	Met Office Hadley Centre, United Kingdom	192 × 144

other models. In contrast, most CMIP6 models do not perform very well in representing historical precipitation. The correlation coefficient is between 0.2 and 0.7, RMSE is between 0.9 and 1.5 and the standard deviation is around 1. The correlation coefficients of only three models including EC-Earth3, EC-Earth3-Veg, and IPSL-CM6A-LR are greater than 0.6. These three models along with CMIP6 mean were taken out for future investigation as shown in Fig. 2.23. It shows that the annual total precipitation of the APHRODITE is around 1200 mm whereas the annual total precipitation of three CMIP6 models and model mean are around 1450–1550 mm. This indicates that even the best CMIP6 models overestimate precipitation by more than 25% and most CMIP6 models do not perform well in precipitation estimation in the southeast Asian region. Therefore, in this study, precipitation projections are not further evaluated for the future scenarios for the LMRB. Dynamic downscaling or bias correction techniques can be applied to derive better precipitation simulations in the future but they are beyond the scope of this study.

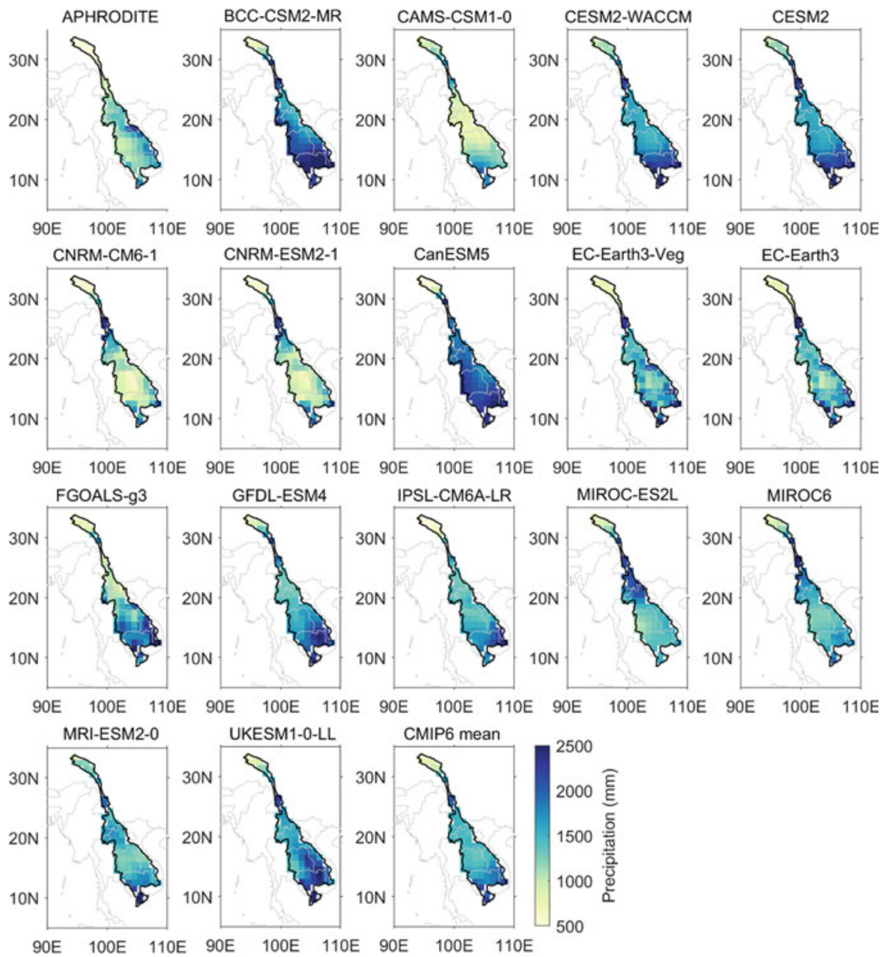

Fig. 2.20 Spatial distributions of annual total precipitation from 16 CMIP6 models, ensemble averages, and APHRODITE observations over the LMRB for the 1995–2014 average

Figure 2.24 shows 10-year moving average values for annual mean temperature for the ensemble of the 16 models and for the observations. The analysis shows that the observed annual mean temperature lies within the 5th–95th percentile range of CMIP6 multi-model ensembles, implying that there is consistency between the observed record and the CMIP6 models. Additionally, the CMIP6 historical simulations can reproduce the observed annual temperature warming trends in the LMRB, although with a slight positive bias.

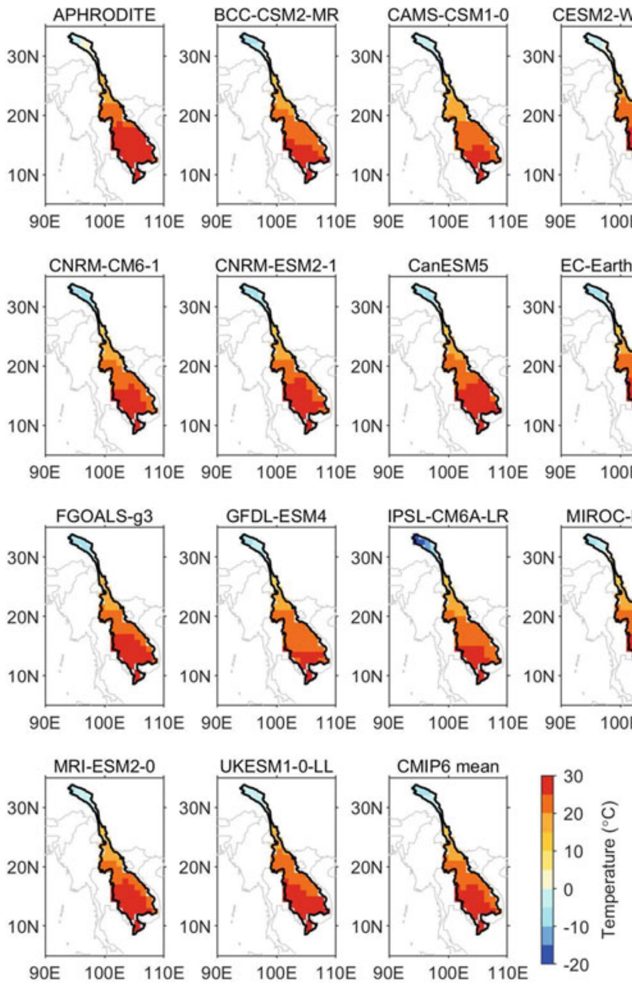

Fig. 2.21 Spatial distributions of annual mean temperatures from 16 CMIP6 models, ensemble averages, and APHRODITE observations over the LMRB for the 1995–2014 average

2.4.2 Projected Changes in Temperature for the Twenty-First Century

2.4.2.1 Annual Mean Temperatures

In this section, future changes in temperature over LMRB in the twenty-first century under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 pathways were presented. Figure 2.25 depicts the spatial patterns of climatological changes in mean temperature, utilizing multi-model ensemble averages for two distinct periods, mid-century

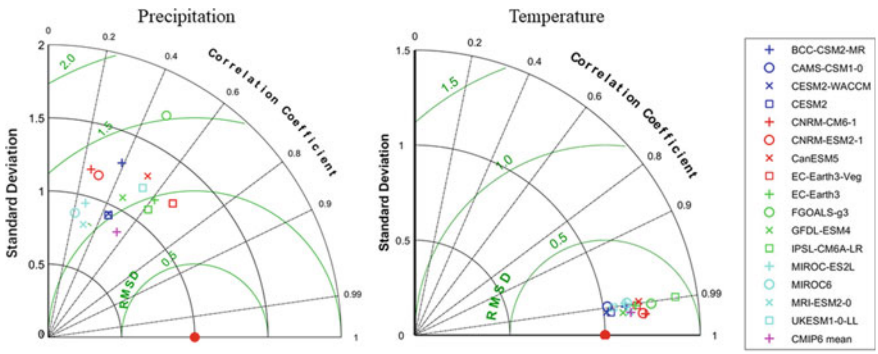

Fig. 2.22 Taylor diagrams for climatological of annual precipitation and temperature over the LMRB comparing each of the CMIP6 models and the observations for the period 1995–2014. The radial coordinate is the magnitude of the standard deviation (denoted by black arcs). The concentric green semi-circles denote root-mean-square difference (RMSD) values. The angular coordinate shows the correlation coefficient (denoted by dotted black lines)

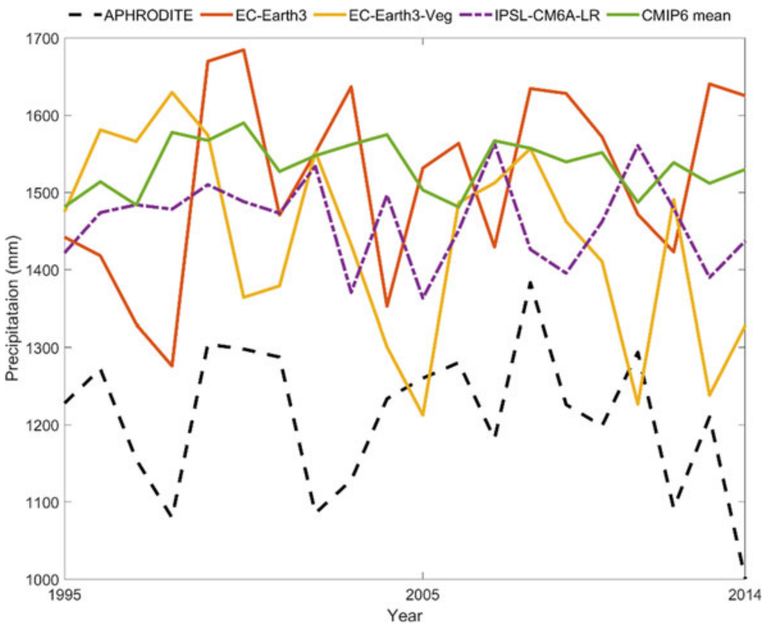

Fig. 2.23 Annual total precipitation for the three best models (correlation coefficient >0.6), CMIP6 model mean and APHRODITE for 1995–2014

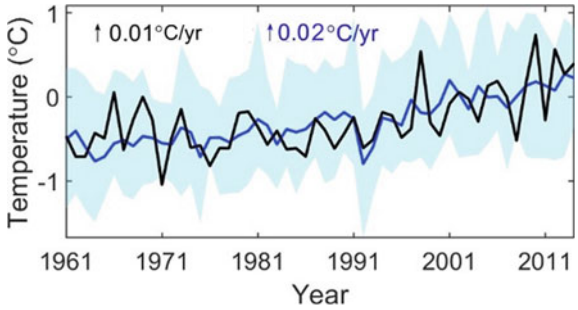

Fig. 2.24 Time series of 10-year moving average annual surface mean temperature from the CMIP6 models and APHRODITE observational dataset during 1961–2014 (blue line and shading: CMIP6; black line: APHRODITE). The trends are calculated for the observations and the CMIP6 ensemble mean during 1961–2014. The shading indicates the ensemble spread (range between the 5th and 95th quantiles). The liner trends are given on top of the time series

(2041–2060) and end of the century (2081–2100), relative to the baseline (1995–2014). The multi-model ensemble mean has been developed for assessing the projected changes.

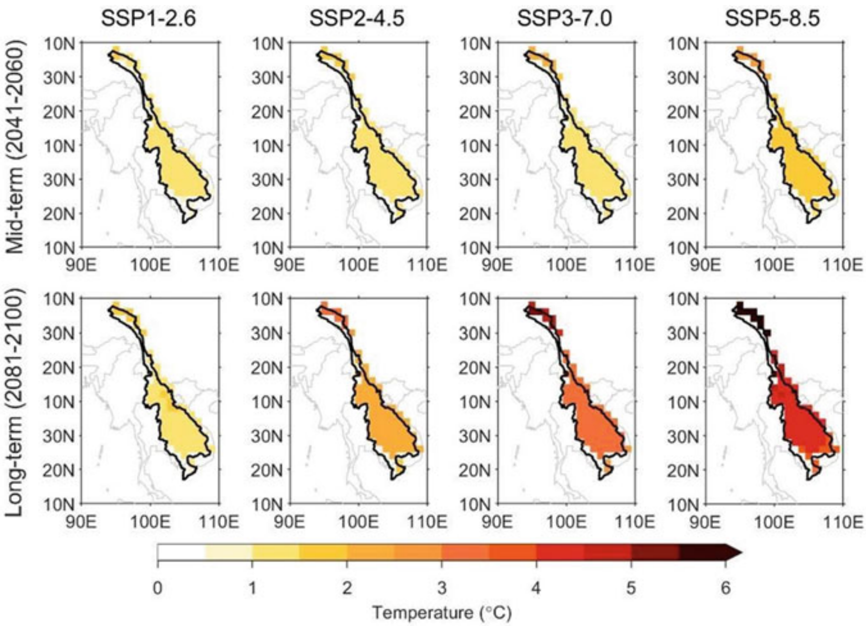

Fig. 2.25 Spatial distribution of changes in annual mean temperature over the LMRB in mid- (2041–2060) and long-term (2081–2100) periods of the twenty-first century, relative to 1995–2014, under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. Unit: °C

Projections from the CMIP6 ensemble mean indicate a persistent trend of temperature elevation across the LMRB. In the simulations, the Lancang River Basin will undergo the greatest absolute temperature increases, while the Southern Mekong River Basin will experience weaker warming. Throughout the mid-term period (2041–2060), different scenarios do not lead to dramatically changed temperature responses under SSP1-2.6, SSP2-4.5, and SSP3-7.0, with most regions observing a temperature elevation lesser than 1.5 °C. However, under the SSP5-8.5 scenario, the temperature increase is generally about 2.0 °C over the Basin, and the increase exceeds 2.0 °C in the Lancang River. By the end of the this century (2081–2100), the projected annual mean temperature increase is significantly larger than the increase for the mid-term period (2041–2060) in all four scenarios. Meanwhile, the increasing temperatures under the SSP5-8.5 and SSP3-7.0 scenarios are more pronounced than under SSP2-4.5 and SSP1-2.6. The temperature changes under the low-forcing sustainability pathway (SSP1-2.6 scenario) are relatively small, with increases generally remaining within 2.0 °C. Compared with SSP1-2.6, ubiquitous temperature increases of 0.7–1.7 and 1.7–3.5 °C are apparent under the SSP2-4.5 and SSP3-7.0 projections, respectively. Additionally, under the SSP5-8.5 scenario, the increase exceeds 4.0 °C over most of the LMRB, and it exceeds 6.0 °C over the Lancang River Basin.

Temporal evolution from 1901 to 2100 of the annual mean temperature changes derived from the multi-model mean over the LMRB is shown in Fig. 2.26, together with their inter-model spreads. All the scenarios exhibit significantly increasing temperatures during the twenty-first century. The SSP5-8.5 scenario exhibits the largest increasing trend, at a rate of 0.06 °C/yr. The SSP3-7.0 and SSP2-4.5 scenarios each show a smaller increasing trend, at a rate of 0.04 and 0.03 °C/yr, respectively. As the lowest-pathways scenario, the SSP1-2.6 experiment projects the lowest rate (0.02 °C/yr) of temperature increase.

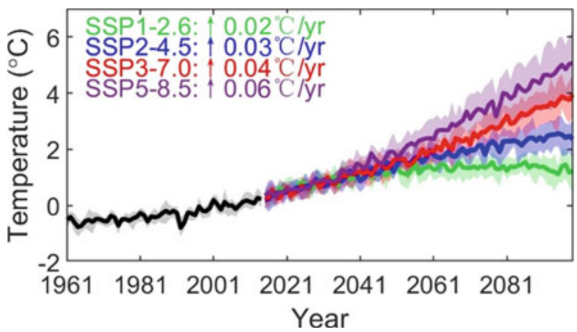

Fig. 2.26 Time series of changes in annual mean temperature over the LMRB during 1961–2100 relative to the period 1995–2014. The black, green, blue, red, and purple curves represent the results of the CMIP6 ensemble mean for the historical period and for the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. The shaded areas are the spreads from the 25th to the 75th percentiles of the annual mean temperatures

2.4.2.2 Projected Changes in Seasonal Temperatures

To further quantify the seasonal temperature changes with respect to the historical period for mid- and long-term periods of the twenty-first century under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, the seasonal temperature changes were summarized and compared by boxplots (Fig. 2.27), where the inter-model range is represented by the vertical whiskers in the box. In general, the seasonal temperature changes show a large and continuous increase with the increase of future emissions, and the uncertainty ranges also gradually increase. For both mid-term and long-term periods, spring (March–May, around 5.6 °C under SSP5-8.5) and summer (June–August, around 5.1 °C under SSP5-8.5) show greater temperature changes than winter (December–January, around 4.5 °C under SSP5-8.5) and fall (September–November, around 3.9 °C under SSP5-8.5) relative to historical periods. Under the scenarios of SSP2-4.5, SSP3-7.0, and SSP5-8.5, the temperature changes of the four seasons in the long-term period will increase significantly compared with that in the mid-term period. For SSP1-2.6, the CMIP6 models exhibit few temperature increases between the long-term period and the mid-term period. And in winter and summer, CMIP6 models show a smaller model range of temperature increases in the long-term period than mid-term period, which indicates a smaller uncertainty in long-term projections under SSP1-2.6.

Figure 2.28a, b show the pattern of the CMIP6 mean inter-seasonal temperature changes for the mid- and long-term period, respectively. For RCP4.5, the CMIP6 mean displays the possibility of large temperature increases during December, January, April, and May under four future scenarios, and smaller increases during July and August. The CMIP6 mean projects quite a large increase in temperature during the long-term period under SSP2-4.5, SSP3-7.0, and SSP5-8.5. It can be seen from Fig. 2.28b that the largest increase in temperature (greater than 4.5 °C under SSP5-8.5) is projected for April and May, while temperatures increase by smaller amounts (around 4.0 °C under SSP5-8.5) in July and August. In the SSP1-2.6 case, the CMIP6 mean shows the possibility of a lower increase in temperature than those under the medium and high future scenarios.

2.4.2.3 Projected Changes in Temperature Extremes

Four temperature extremes indices (Table 2.5), as recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI), have been chosen to evaluate future changes in daily maximum (TX) and daily minimum (TN) temperatures from 1951 to 2099. These encompass three hot indices (annual maximum value of TX, TXx; the percentage of warm days, TX90p; and the percentage of warm nights, TN90p) and one cold index (annual minimum value of TN, TNn), which together can characterize the intensity and frequency of temperatures extremes.

Figures 2.29 and 2.30 depict the spatial distributions of projected changes in indices of temperature extremes over the LMRB during the mid- and long-term periods of the twenty-first century. Each index of extreme temperatures is are

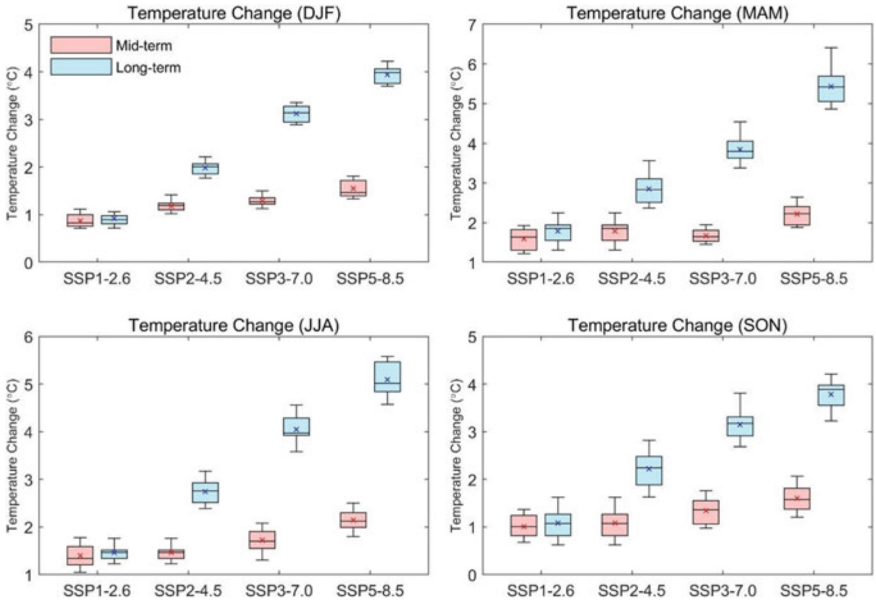

Fig. 2.27 The box and whisker plots show seasonal temperature changes for mid-term (2041–2060) and long-term (2081–2100) periods of the twenty-first century with respect to the base period 1995–2014 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. Boxes indicate the interquartile model spread (25th and 75th quantiles), with the horizontal line indicating the ensemble median and the whiskers showing the total inter-model range. The ensemble means are indicated using red and blue crosses

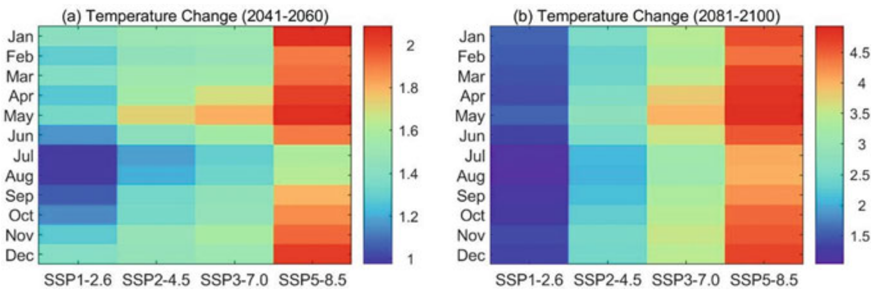

Fig. 2.28 Inter-seasonal temperature changes illustrated by the multi-model ensemble for **a** mid-term (2041–2060) and **b** long-term (2081–2100) periods of the twenty-first century, relative to 1995–2014, under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. Unit: °C

projected to show prominent increases over the LMRB, exhibiting more intense warming in the SSP5-8.5 scenario. For TXx, The most remarkable warming is predominantly projected in the Lancang River Basin. Relative to the reference period, the mid-term and long-term warming of TXx in SSP5-8.5scenario increased by around 2.5 and 5.0 °C, respectively. Regarding TNn, the most intense warming

Table 2.5 Definitions of the extreme temperature indices employed in this section

Label	Index name	Index definition	Units
TXx	Max TX	Annual maximum value of daily maximum temperature	°C
TNn	Min TN	Annual minimum value of daily minimum temperature	°C
TX90p	Warm days	Percentage of days when the daily maximum temperature is above the 90th percentile for the base period 1961–1990	%
TN90p	Warm nights	Percentage of days when the daily minimum temperature is above the 90th percentile for the base period 1961–1990	%

also occurs in the Lancang River Basin in the future scenarios, with magnitudes of around 3.5 and 8.0 °C under the SSP5-8.5 scenario during the middle and end parts of this century, exceeding the increases in TXx. A pronounced increase in warm days (TX90p) and warm nights (TN90p) is projected to increase greatly over the southern Mekong River Basin under all SSP scenarios (around 80 and 100% for SSP5-8.5, respectively) by the end of the twenty-first century. The robust projected increases of these four indices over the LMRB suggests a potential risk of intensified temperature extremes adversely affecting natural and social systems, in light of accelerated emission trajectories. Nevertheless, consistent with the changes in mean temperatures previously discussed, the indices of extreme temperatures also appear to exhibit minimal variations over time under the SSP1-2.6 scenario, reflecting the potential efficacy of anticipated climate mitigation and adaptation strategies associated with this scenario.

To identify the inter-annual variability under different scenarios, Fig. 2.31 show the temporal evolution of regional average annual temperature extremes indices over the LMRB during 1961–2099. Generally, the CMIP6 models exhibit increasing trends in annual TXx, TNn, TX90p, and TN90p throughout the twenty-first century. Across all scenarios, a more pronounced enhancement is observed in TXx relative to TNn. By twenty-first century end, the multi-model mean projected increases in TXx and TNn are, respectively, 0.01 and 0.01 °C/yr in SSP1-2.6, 0.03 and 0.03 °C/yr in SSP2-4.5, 0.05 and 0.05 °C/yr in SSP3-7.0, and 0.07 and 0.06 °C/yr in SSP5-8.5. The increasing trends of TN90p are greater than that of warm days (TX90p), likely due to amplified water vapour and radiative feedbacks at lower air temperatures. Towards the end of the twenty-first century, the warming trends for TX90p and TN90p over the Basin are 0.15 and 0.20%/yr for SSP1-2.6, 0.38 and 0.45%/yr for SSP2-4.5, 0.57 and 0.57%/yr for SSP3-7.0, and 0.69 and 0.72%/yr for SSP5-8.5.

It is noticed that the observed trend of TNn is larger than that of TXx (Figs. 2.9b and 2.11b), but the simulated future changes of TXx are higher than those of TNn (Fig. 2.13). In fact, the observed warming is much faster in TN (homogeneously) than the TX, which is similar to the observed change in global temperature as shown in IPCC AR6 (Fig. 11.2 in Chap. 11 of IPCC AR6). This is associated with a decrease in the diurnal temperature range (DTR). Various localized factors such as cloud cover,

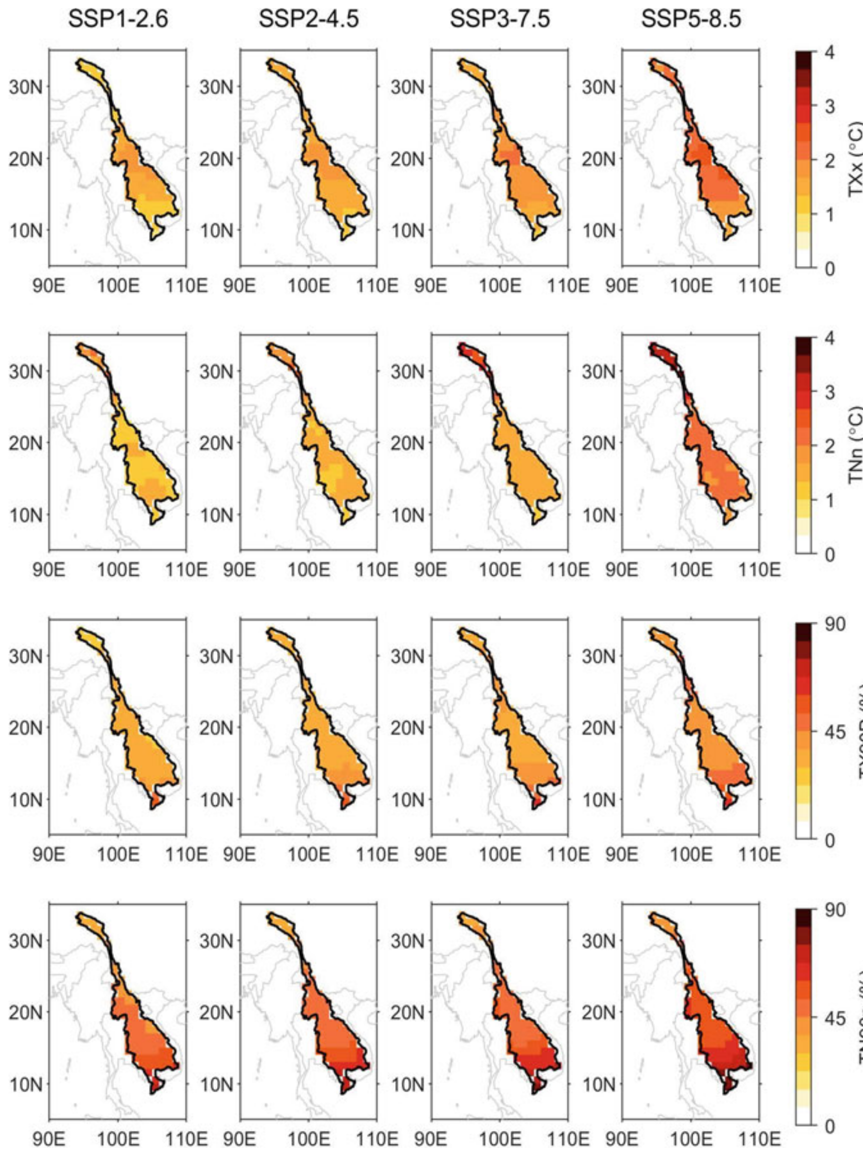

Fig. 2.29 Spatial distributions of projected changes in annual mean max TX (TXx), min TN (TNn), warm days (TX90p), and warm nights (TN90p) for the mid-term (2041–2060) period relative to the reference period 1995–2014 under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. Note that TX90p and TN90p are displayed as absolute exceedance rates

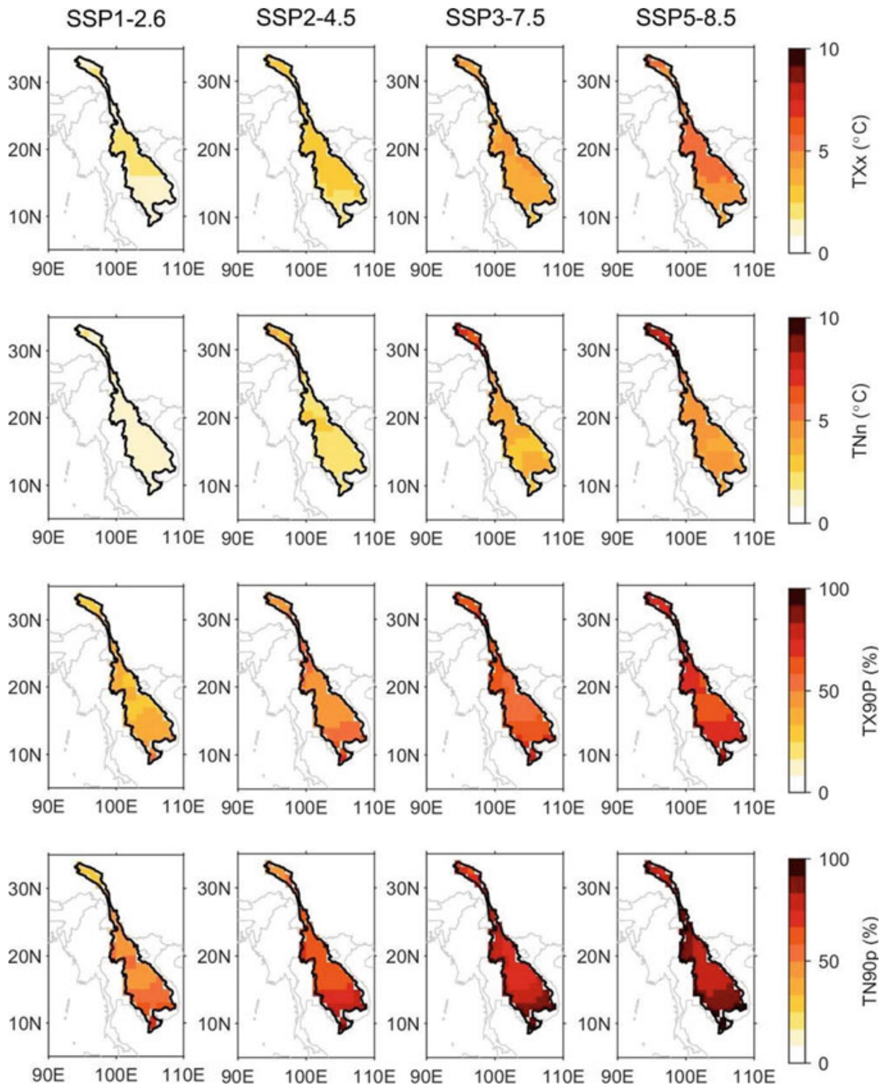

Fig. 2.30 Spatial distributions of projected changes in annual mean max TX (TXx), min TN (TNn), warm days (TX90p), and warm nights (TN90p) for the long-term (2081–2100) period relative to the reference period 1995–2014 under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. Note that TX90p and TN90p are displayed as absolute exceedance rates

soil moisture, and precipitation significantly influence the DTR variations (Davy et al., 2017). Future projections imply that modifications in these local conditions could potentially amplify the DTR, marking a reversal from the current observed patterns.

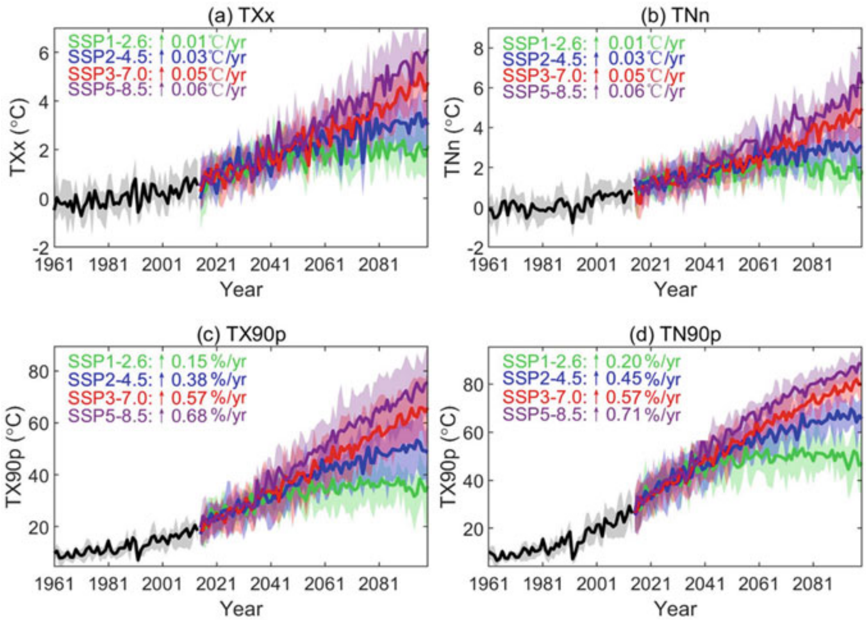

Fig. 2.31 Time series of changes in annual mean max TX (TXx), min TN (TNn), warm days (TX90p), and warm nights (TN90p) over the LMRB during 1961–2100 relative to the period 1995–2014. (Note that the time series for TX90p and TN90p are displayed as an absolute exceedance rate). The black, green, blue, red, and purple curves represent the results for the CMIP6 ensemble mean for the historical period and the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. The shaded areas are the spreads from the 25th to the 75th percentiles of the annual mean temperature extreme indices

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Chapter 3
Surface Water

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Abstract This chapter assesses surface water changes due to climate change and human activities, by particularly examining runoff and streamflow. Changes in the hydrological cycle due to climate change and human intervention can lead to

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diverse environmental impacts and risks. Fresh water is the agent that delivers many of the impacts of climate change on society. As the major component of freshwater systems, surface water has been significantly altered across basins in terms of spatial and temporal characteristics. The comprehensive understanding of the current status of surface water in the LMRB, such as the distributions and patterns of runoff changes across the Lancang-Mekong River Basin was completed through the high-resolution river network extraction and sophisticated hydrological models. **Significant but different trends were found in the seasonal and annual runoff from the LMRB due to different reasons. Over the period of 1971–2010, the annual streamflow shows a general downward trend due to the continued enhancement of human activities.** Runoff in the dry season is found to increase faster than the mean annual runoff. As for the spatial distribution, significant trends in streamflow were observed mainly in the middle basin and east of the lower basin. Superimposed on the substantial seasonal cycles is the noticeable lake shrinkage in recent years, especially the Tonle Sap Lake. Evidently decreased inundation was found in most years in the recent two decades from 2000 to 2018. An evident decreasing trend in runoff caused by climate change in the high correlation zone of the Tonle Sap Lake, mainly due to the precipitation decreasing, indicates that climate change contributed to the decrease in water level in the Tonle Sap Lake in addition to human activities. In addition to the decreases in the runoff, streamflow and water level in the Tonle Sap Lake, a significant ($p < 0.05$) downward trend in the baseflow was also found from 1980 to 2007. **Unlike the historical changes in runoff, previous studies projected with high confidence an increasing trend for streamflow in the LMRB, regardless of the climate forcings and models used.** However, the flow regime is highly susceptible to a variety of drivers, e.g., dam construction, irrigation expansion, land-use change and climate change. Substantial changes are expected in both annual and seasonal flow, along with a generally increasing trend. Although hydropower development exhibits a limited influence on total annual flows, it has the largest seasonal impact on streamflow, with an increase in the dry season and a decrease in the wet season, by outweighing those of the other drivers.

3.1 Introduction

Despite rich water resources (~8,000 m^3/cap/yr), the LMRB faces significant challenges due to the high variability in runoff, both in terms of timing and location (MRC, 2010). It is imperative to comprehend how runoff patterns respond to the impacts of climate change and human interventions. This understanding is crucial for ensuring the availability of water, food, and energy resources in the region, as well as for achieving long-term sustainability. Therefore, a thorough assessment of changes in the runoff regime of the LMRB is necessary to assist in understanding the influence of regional climate changes and human activities on water availability.

The LMR originates in the Tibetan Plateau, a region that is extremely sensitive to climate change (Chen et al., 2015; Kuang & Jiao, 2016). Climate change has already left a significant imprint on the hydrology of the LMRB in recent decades (Lyon et al., 2017; Phi Hoang et al., 2016). Over the past half century, the basin has experienced increased temperatures as well as increased rainfall during the flood period and reduced rainfall during the dry period. Additionally, the rapid economic growth, rising food demands, and increasing energy requirements in riparian countries have driven substantial changes in land use and land cover, especially due to extensive agricultural expansion and hydropower development across the basin (Johnston & Kummu, 2012). Climate change and human interventions have substantially reshaped the basin's runoff patterns, resulting in more frequent extreme events and extended dry periods (Thilakarathne & Sridhar, 2017). The lack of upstream inflow during the dry season exacerbates the risk of saltwater intrusion, impacting downstream delta ecosystems, domestic water supplies, and agricultural production (Smajgl et al., 2015). Simultaneously, intense and widespread precipitation events have led to severe flooding, causing damage to crops and infrastructure, and disrupting the functions of the downstream delta (Cosslett & Cosslett, 2014).

The changes in the runoff regime of the basin have led to the degradation of essential natural resources in the region, including fish, water, and land, upon which millions of people depend (Chea et al., 2016). In addition, the climate change impact on water has been projected to intensify in the near future, and the spatial and year-to-year distribution will be more uneven in the basin (Hoang et al., 2019). Superimposed by the effects of human activities, thereby challenging sustainable development in the region. Therefore, there is an urgent need to deepen our understanding of changing runoff patterns to facilitate collaborative efforts across borders and synthesize scientific advancements for the benefit of the region's sustainable future.

3.2 Runoff Changes in the Basin

3.2.1 River Networks Geometry in the Basin

The geometry of river networks fundamentally constrains the discharge process and thus has prominent impacts on water resource distribution. An expanded role for river networks is increasingly recognized due to more evidence that small streams process and store considerably more terrestrial materials than previously thought. However, the attempts to elucidate changes in terrestrial materials, including runoff, in a basin have been limited by modelling and observation at coarse resolutions. With Earth Observation (EO) data increasingly available, this section presents a novel imagery-based methodology to measure the geometry of river networks at finer resolutions and of more dimensions. Using the proposed methodology, the high-resolution river network geometric features including river networks, surface area, width, and depth have been delineated, which contribute to a more complete understanding of the distributions and patterns of the runoff changes across the LMRB.

3.2.1.1 River Networks

The extraction of river networks plays a pivotal role in addressing fundamental inquiries pertaining to the hydrological dynamics of a watershed's surface. This practice, deeply rooted in the field of hydrology, has traditionally been employed for the purpose of river flow modeling (David et al., 2011; Lin et al., 2018; Yamazaki et al., 2013). Nevertheless, the utilization of high-resolution drainage networks has seen a steady rise, finding applications not only in the realm of large-scale hydrological predictions but also in spatially comprehensive research endeavors. These include the evaluation of flood inundation, dam failure scenarios, and reservoir operations (Lehner & Grill, 2013; Shin et al., 2020; Yamazaki et al., 2019). Such applications hold particular significance in enhancing our comprehension of runoff patterns and water resource management within the watershed.

To extract high-resolution river networks for the LMRB that further facilitate surface water assessments, a new method is proposed, namely Remote Sensing Stream Burning (RSSB) (Wang et al., 2021). Enabled by RSSB, the basin-scale drainage networks are extracted at the highest 10-m resolution with the integration of Sentinel-2 imagery (Fig. 3.1). Compared to river networks, drainage networks provide additional flow information, such as flow direction and flow accumulation.

Table 3.1 illustrates the distribution of river length and river network density for drainage networks extracted using the RSSB method. It is observed that both river length and network density exhibit a general adherence to the conventional power law pattern, as documented by Leopold and Maddock (1953). Of particular note is the high-resolution approach, which successfully delineates nine stream orders (ω = 9) in contrast to the coarse-resolution method. This observation underscores the efficacy of the newly proposed technique, as it not only enhances the accuracy of

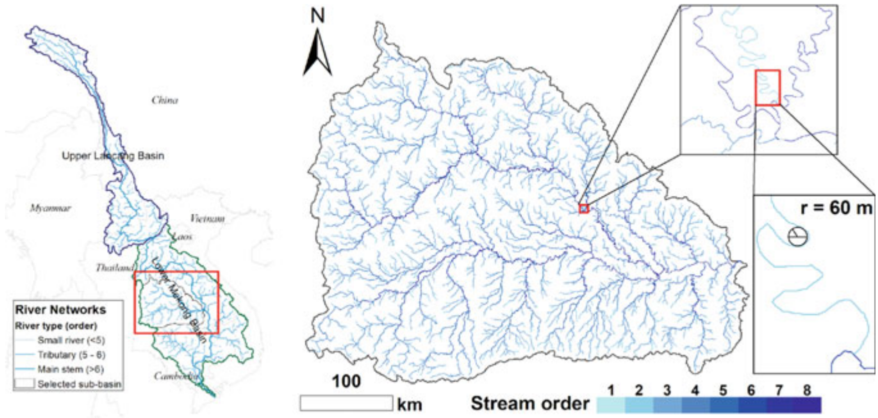

Fig. 3.1 Lancang-Mekong River networks extracted by RSSB (r represents the curvature radius of a meander). The river order is shown in Strahler stream order

Table 3.1 Statistics of Lancang-Mekong River networks, including stream order ω (in Strahler order), number n_{ω}, mean length L_{mean}, total length L_{total}, and the river networks density D

Order (ω)	Lancang-Mekong river networks			
	n_{ω}	L_{mean} (km)	L_{total} (km)	D (km km^{-2})
1	516,095	0.19	97,756	0.815
2	239,744	0.19	44,963	0.375
3	132,648	0.18	23,922	0.199
4	77,973	0.17	13,073	0.109
5	42,178	0.16	6,891	0.057
6	21,331	0.16	3,450	0.029
7	10,623	0.16	1,676	0.014
8	5,152	0.14	744	0.006
9	2,831	0.15	431	0.004
Total	1,048,575	0.18	192,907	

flowline representation but also substantially augments the level of detail within the network.

3.2.1.2 Surface Water Area

Surface water area is one of the most perceivable indicators of water resources, offering a means to conduct quantitative assessments of human-induced modifications within a watershed, such as the linkage between river engineering and lake losses, and the coupling of water loss with long-term droughts (Pekel et al., 2016). Such applications aid in categorizing transitions in land surfaces, including conversions from land to water, water to land, the permanence of land, or the enduring presence of water, as described by Donchyts et al. (2016). These analyses provide essential support for research and evaluations related to flood inundation, land reclamation, and sea-level rise, particularly in regions of environmental and societal significance (Müller et al., 2016). Additionally, the detection of water plays a pivotal role as an initial step in numerous applications, including the mapping of land-use and land-cover (Arino et al., 2012; Chen et al., 2014), predicting waterborne epidemic disease (Smith et al., 2013), managing flood hazards, estimating water scarcity and assessing water quality (Dottori et al., 2016; Liu et al., 2016; Olmanson et al., 2016; Vanham et al., 2018).

The surface water area of the basin is highly fluctuating (Fig. 3.2). The total surface water area estimated by MuWI method based on both Landsat and Sentinel-2 data (Wang et al., 2018) is approximately between 20,000 and 30,000 km^2. Variations in surface water area are generally synchronized with the flood and drought cycle in the basin. For example, a devastating flood occurred in 2000 when the surface

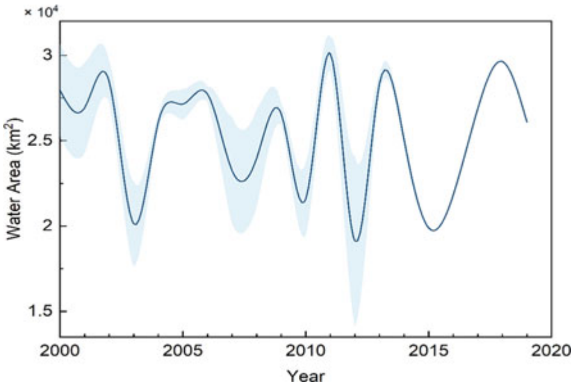

Fig. 3.2 The total monthly surface water area in Lancang-Mekong River basin

water area was high, while the 2015 drought, the most severe drought in the past three decades, coincided with a low surface water area. The frequency of the cycle appears to have decreased and stabilized in the past decade, which may imply that the regulation capacity of the increasing number of dams has come into effect.

Surface water areas are disproportionally distributed in the six countries within the transboundary basin (Fig. 3.3). Although more than one fifth (21.5%) of the basin lands are located in China, China shares an insignificant portion of the total surface water area (3–5%). In contrast, the downstream country, Cambodia, holds less basin land than China, but accounts for the most surface water area (55–60%) among the six countries.

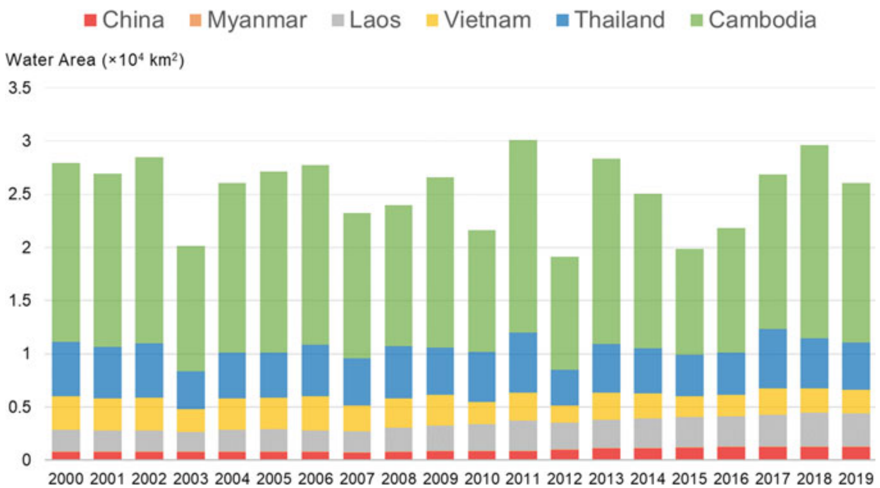

Fig. 3.3 The yearly average surface water areas of six countries in the Lancang-Mekong River basin

3.2.1.3 River Width and Bathymetry

The river width and river bathymetry (depth) are the two fundamental geometric dimensions of the river networks. The river expands geometrically downstream due to erosion from the accumulated flow. This geometric expansion with the increasing flow often follows a power-law relationship, which is recognized as the well-known theory of hydraulic geometry (Leopold & Maddock, 1953). The river width and depth of the LMR (Fig. 3.4) follow the pattern of expansion in general where the magnitude of the major stem is considerably larger than tributaries.

In particular, the LMRB is characterised by diverse fluvial geomorphology with valley-constrained regions upstream and bedrock-constrained areas downstream (Meshkova & Carling, 2012). The gradient of the upper Lancang River is approximately 2 m/km, more than ten times that of the lower Mekong River, indicating that more convergent topography exists upstream while divergent but well-defined banks are prevalent downstream (Pokhrel et al., 2018a, 2018b). Therefore, the upstream river channels are relatively narrow but deep.

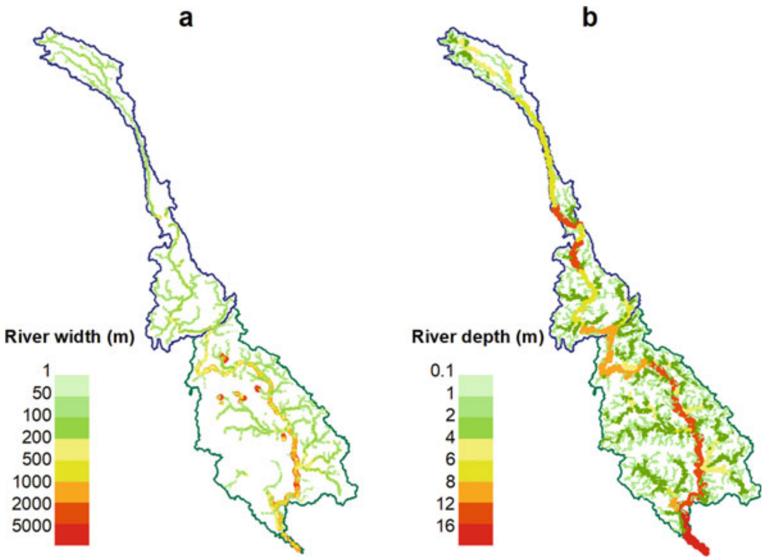

Fig. 3.4 Width and depth of the Lancang-Mekong River

3.2.2 Runoff Modelling in the Basin

3.2.2.1 Runoff Simulation with WAYS

Hydrological models are the most common tools for runoff simulation. They simplify the characterisation of real-world systems and describe the rainfall–runoff relations. Hydrological components and water storage in land surface, soil, and groundwater reservoirs are idealised in the model (Bierkens, 2015). In the basin considered here, the runoff is simulated by a sophisticated large-scale hydrological model, WAYS (Water And ecosYstem Simulator) that considers the spatial heterogeneity of the root zone during the hydrological simulation (Mao & Liu, 2019). The WAYS model is developed by the core members of the Strategic Priority Research Program of the Chinese Academy of Sciences "*Climate Change and Water Resources in the Great River Regions in Southeast and South Asia*" (project number XDA 20060400), and is tailored for the hydrological processes modelling in the basin.

WAYS is a process-based hydrological model, implemented in Python, which assumes water balance at the grid cell level and simulates the hydrological processes in a fully distributed way. The WAYS model works on a daily time step, and the model structure consists of five conceptual reservoirs: the snow reservoir Sw (mm) representing the surface snow storage, the interception reservoir Si (mm) expressing the water intercepted in the canopy, the root zone reservoir Sr (mm) describing the root zone water storage in the unsaturated soil, the fast response reservoir Sf (mm), and the slow response reservoir Ss (mm). Two lag functions are applied to describe the lag time from the storm to peak flow (TlagF) and the lag time of recharge from the root zone to the groundwater (TlagS). In addition to the water balance equation, each reservoir also has process functions to connect the fluxes entering or leaving the storage compartment (so-called constitutive functions). A schematic representation of how the hydrological processes are modeled in WAYS is shown in Fig. 3.5. Traditional hydrological models simulated soil hydrology with a layer-based scheme that cannot reflect the influence of the heterogeneity in the root zone, but the WAYS model assimilates the separately derived root zone storage capacity and thus is able to consider the impacts of the spatial heterogeneity of root zone in soil hydrology. More details about WAYS can be found in Mao and Liu (2019).

Using the newly developed WAYS model, some basic hydrological variables, such as precipitation, temperature, and specific humidity, were simulated from 1971 to 2010. The WAYS model depicts the dynamics of the hydrological variables every day at a spatial resolution of 0.5°, which allows for an in-depth understanding of the changes in the hydrological system, including the runoff changes. In order to more intuitively represent the dynamics of the simulated hydrological variables in the entire basin, the variables are averaged from a daily scale to a monthly scale, which is shown in Fig. 3.6. In addition, the spatial pattern of the hydrological variables can also be revealed based on the simulations (see Fig. 3.7).

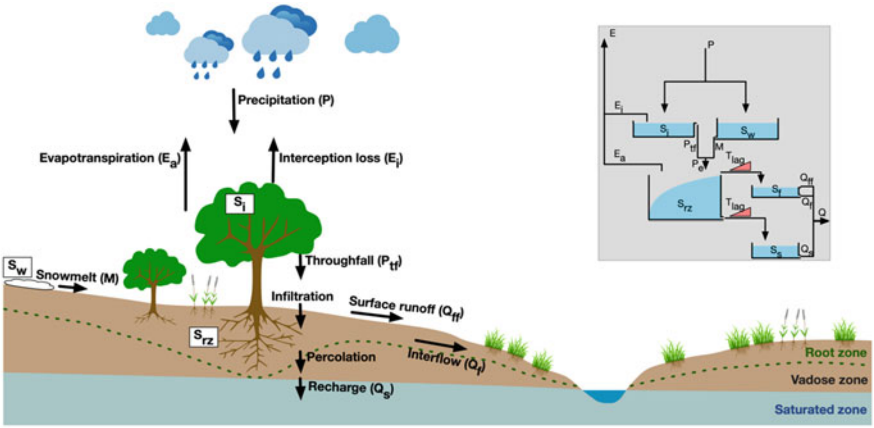

Fig. 3.5 Model structure of the WAYS model (Mao & Liu, 2019)

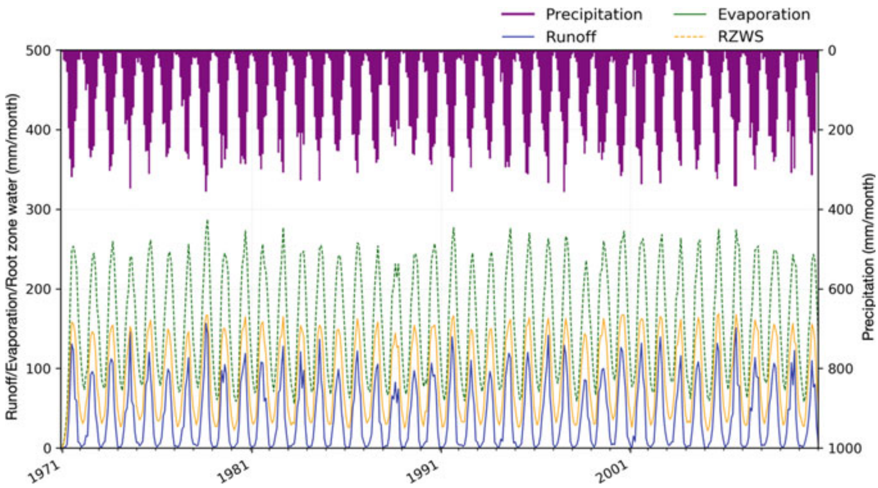

Fig. 3.6 The observed (precipitation) and simulated (Runoff, Evaporation, and Root Zone Water Storage (RZWS)) time series of fundamental hydrological variables at a monthly scale

3.2.2.2 Runoff Simulation with a Multi-model Framework

In addition to the WAYS model, nine other state-of-the-art large-scale models (CLM4, DBH, H08, LPJmL, MATSIRO, MPI-HM, PRC-GLOBWB, VIC, and WaterGAP2) were applied to simulate the runoff for uncertainty assessment. Including the WAYS model, all the selected models participated in the second phase of the Inter-Sectoral Impact Model Inter-Comparison Project, which offers a framework for consistently investigating the impacts of climate change across affected sectors and spatial scales (ISIMIP2a) (Warszawski et al., 2014). All models were driven by

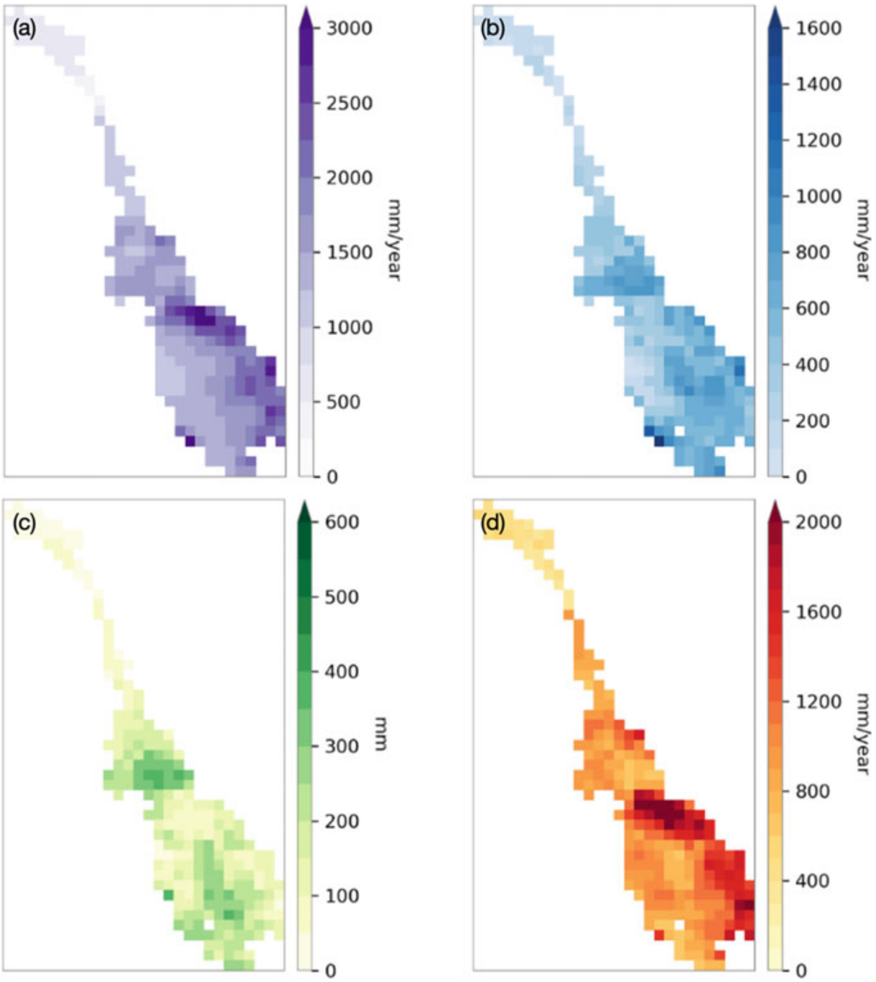

Fig. 3.7 The spatial pattern of the observed and simulated annual hydrological variables: **a** precipitation, **b** runoff, **c** root zone water storage, **d** evaporation

the same climate forcing (Global Soil Wetness Project Phase 3 data) (GSWP3) using a spatial resolution of 0.5° from 1 January 1971 to 31 December 2010 on a continuous run on a daily scale. The GSWP3 dataset was generated based on the 20th Century Reanalysis Project, and has been widely used in several studies conducting hydrological simulations (Masaki et al., 2017; Tangdamrongsub et al., 2018; Veldkamp et al., 2017). The WaterGAP and WAYS models were calibrated prior to the hydrological simulation (Alcamo et al., 2003; Mao & Liu, 2019), while the other eight models were not calibrated specifically for the ISIMIP2a simulations, and their default model parameters were therefore used in the runoff simulations. All models were treated as independent, although many of them shared similar structures and parameterisations:

for example, some were similar with respect to their fundamental approach to simulating evapotranspiration, representing water exchanges in soil across the basin, and modelling snow melting. The basic differences in the models with respect to simulating land-surface hydrological processes are presented in Table 3.2, and detailed descriptions of the models applied in this work are provided by references associated with each model cited in the table.

To assess the accuracy of the hydrological models, a rigorous verification process was conducted. Monthly runoff data from the International Satellite Land Surface Climatology Project Initiative II University of New Hampshire/Global Runoff Data Centre (ISLSCP II UNH/GRDC) were employed for validation purposes. These data, available at a spatial resolution of 0.5° and spanning the period from 1986 to 1995, served as a benchmark for evaluating the performance of model simulations within the basin. The ISLSCP II UNH/GRDC dataset, often referred to as UNH-GRDC, is a composite of runoff data generated through a combination of water balance

Table 3.2 Technical description of the ten evaluated global-scale hydrological models

Model	Model type	Snow melt scheme	Evapotranspiration scheme	Number of soil layers	References
CLM4	LSM	Physically based snow module	Monin–Obukhov similarity theory	15	Lawrence et al. (2011)
DBH	LSM	Energy balance method	Energy balance model	3	Tang et al. (2006)
H08	HM	Energy balance method	Bulk approach	1	Hanasaki et al. (2008)
LPJmL	DVM	Degree-day method	Priestley–Taylor	6	Gerten et al. (2004)
MATSIRO	LSM	Energy balance method	Monin–Obukhov similarity theory	13	Takata et al. (2003)
MPI-HM	HM	Degree-day method	Penman–Monteith	1	Stacke and Hagemann (2012)
PRC-GLOBWB	HM	Degree-day method	Hamon	2	van Beek et al. (2011)
VIC	HM	Energy balance method	Penman–Monteith	3	Liang et al. (1994)
WaterGAP2	HM	Degree-day method	Priestley–Taylor	1	Alcamo et al. (2003)
WAYS	HM	Degree-day method	Penman–Monteith	1	Mao and Liu (2019)

LSM Land surface model, *HM* Hydrological model, *DVM* Dynamic vegetation model

model estimates and the assimilation of observed discharge data from gauge stations. While it retains the spatial characteristics of the water balance, it is influenced and constrained by observed records from these monitoring stations (Fekete et al., 2011). Importantly, the UNH-GRDC dataset serves as a standardized reference dataset in the ISIMIP2a initiative for model validation purposes, as established by Warszawski et al. (2014).

Prior to examining changes in runoff patterns, an evaluation of the hydrological models used for runoff simulation was conducted against reference runoff data. This evaluation commenced with an analysis of the models' performance through the simulation of monthly runoff time series. Subsequently, the models' capabilities in replicating runoff at various return periods were assessed. Results indicated that all models were able to replicate the observed monthly runoff time series, and the seasonal runoff cycles were particularly well duplicated by the models. However, relatively large uncertainties were observed in high-value runoff simulations during summer seasons (with a wider spread among the models) in comparison with the low-value simulations (as depicted in Fig. 3.8). Although uncertainties existed in the model simulations, the multi-model ensemble mean agreed well with the reference runoff data. During the evaluation process, the performances of the models were further evaluated using a set of transferrable benchmarks. In order to overcome the problem that, generally, different metrics are only suitable for assessing individual characteristics of a simulated time series, and to enable consistent comparisons, six commonly used metrics were applied (the relative bias, normalised root mean square difference (RMSD), correlation coefficient, normalised standard deviation, centered RMSD, and the Nash–Sutcliffe coefficient of efficiency (NSE)), and some were standardised prior to conducting comparisons. These metrics were then used to assess the relative performance of each model in different aspects, and the results were presented in three types of diagrams (a target, a radar, and a Taylor diagram).

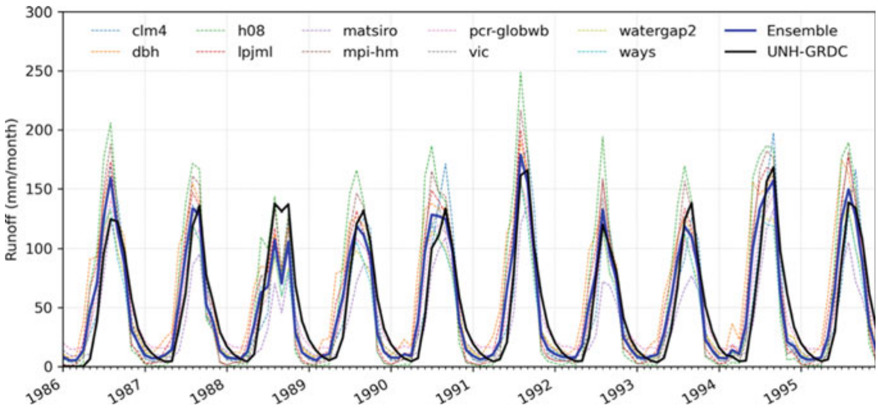

Fig. 3.8 Simulated basin-average monthly runoff time series by ISIMIP2a models (dashed lines), model ensemble mean (solid blue line), and UNH-GRDC runoff reference data (solid black line)

The ten selected models and the multi-model ensemble were evaluated to determine their ability to reproduce the observed monthly runoff time series. In addition, the model simulated monthly runoff time series and the corresponding ensemble mean were compared with reference data (UNH-GRDC runoff data) for the period from 1986 to 1995 (see Fig. 3.8). Results indicated that all models were able to replicate the observed monthly runoff time series, and the seasonal runoff cycles were particularly well duplicated by the models. However, relatively large uncertainties were observed in high-value runoff simulations during summer seasons (with a wider spread among the models) in comparison with the low-value simulations (as depicted in Fig. 3.8). Although uncertainties existed in the model simulations, the multi-model ensemble mean agreed well with the reference runoff data.

Detailed model evaluations revealed that the ensemble mean of the model was better than that of the single model in terms of monthly time series, seasonal cycles, and runoff at different return periods. Particularly, the model ensemble mean was also capable of modelling variability in the runoff time series. Accordingly, the model ensemble mean was used to analyse runoff regime changes in the basin, and then quantify the uncertainty associated with the model based on ten model simulations (Fig. 3.9).

The comprehensive model evaluations unveiled that the model ensemble mean displayed superior performance compared to the individual models in replicating monthly time series, capturing seasonal cycles, and estimating runoff across various return periods. Notably, the model ensemble mean exhibited a remarkable capacity for modeling the variability within the runoff time series. Consequently, the analysis of runoff regime changes within the basin was carried out using the model ensemble mean. Subsequently, assessments were based on the results of the ten individual model simulations to quantify the uncertainties associated with the modeling process.

3.2.3 Historical Changes in Runoff

The changes in watershed runoff in the LMRB are firstly analysed by using hydrological simulations of the ten models. Based on five hydrological indicators, the characteristics of runoff changes within the basin from 1971 to 2010 were investigated. Mean Annual Runoff (MAR) was used to assess the overall runoff changes on a yearly scale and during the wet and dry seasons, respectively. The 95th percentile runoff (Q95) and the 5th percentile runoff (Q5) were applied to assess the high value and low value of runoff changes in the basin, respectively, and the annual 7-day maxima runoff (MAX-7) and annual 7-day minima runoff (MIN-7) were used to appraise the runoff regime changes relating to extreme events (Danneberg, 2012).

Based on the model ensemble mean, the average MAR in the LMRB was approximately 655 mm/yr for the period 1971–2010 and MAR increased by 8.0% (52.61 mm) during this period (Fig. 3.10). However, there was only a slight annual increase in MAR, at an average rate of 0.2% (1.32 mm/yr) and the trend detected was not significant. For the entire basin, different hydrological indicators showed different

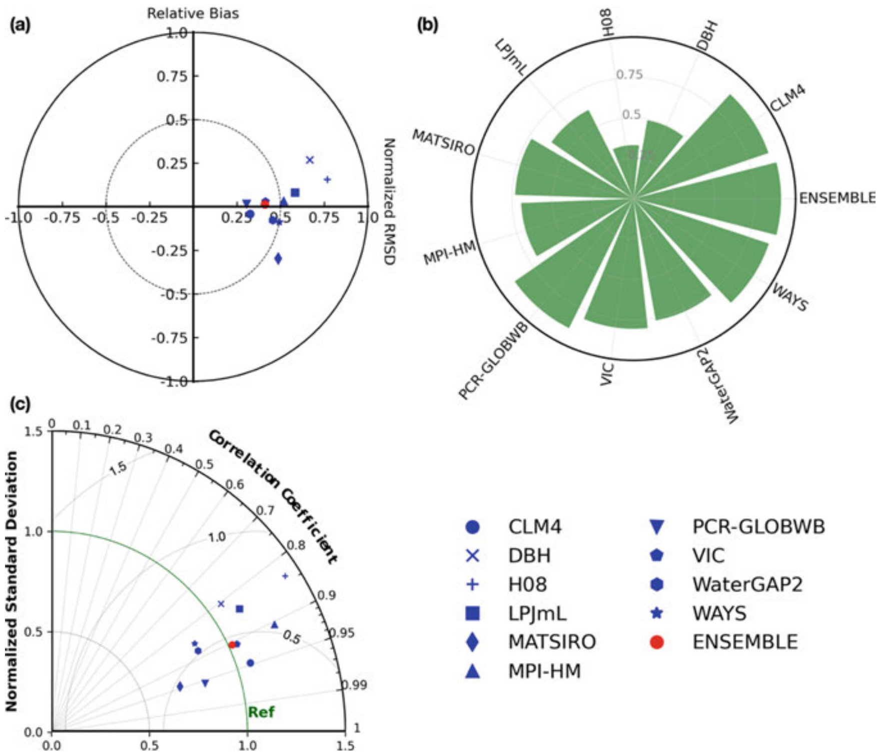

Fig. 3.9 Diagrams showing statistics used in model evaluations: **a** target diagram for relative bias and normalised root mean square difference, **b** radar diagram showing the Nash–Sutcliffe coefficient of efficiency, **c** Taylor diagram showing the correlation coefficient, normalised standard deviation of errors, and centered RMSD

change ratios for the period 1971–2010. All hydrological indicators from all models demonstrated an increasing change trend for the basin, with the exception for MIN7 and Q95 indicators, which exhibited lower runoff values. However, some models demonstrated decreased trends with the median value of multiple models indicating an increasing trend. Models also showed relatively high agreements for change trend detections of MAR, MAX7, Q5, and runoff in the wet season. The highest model agreement was observed with respect to the MAR trend detection, where the smallest spread range was found among model estimates. In contrast, large uncertainties in model estimates were observed for change trend detections of low runoff values (MIN7 and Q95) and runoff in the dry season, particularly the trend in the dry season, which ranged from 7.6 to 34.9%. Overall, although uncertainties existed, the model ensemble mean based estimates indicated that runoff in the basin increased during the period 1971–2010 with respect to low values, high values, MAR, and runoff in both dry and wet seasons. The change in MAR (8.1%) exhibited an increasing magnitude, similar to the changes in MAX7 (8.5%), and Q5 (8.0%), indicating higher runoff. For

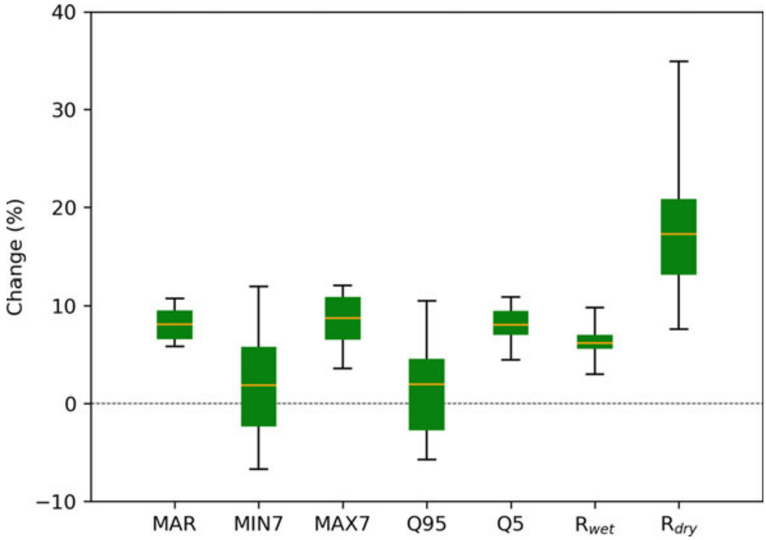

Fig. 3.10 Changes in different hydrological indicators from the ten hydrological model simulations. The box-whiskers represent the 0th, 25th, 50th, 75th, and 100th percentiles of the distribution in changes for each hydrological indicator

the model average, low flow with respect to minimum runoff over seven consecutive days (MIN7) and runoff that exceeded 95% of the time series (Q95) exhibited the lowest increasing ratio with change values of 2.2 and 1.7%. Runoff during the dry season showed the greatest increase (17.7%) for the period 1971–2010, while runoff during the wet season increased slightly (approximately 6.2%).

Spatially, the trend in Mean Annual Runoff (MAR) exhibited a distinct gradient across the basin, with a pronounced increasing trend in both the upper and lower basin areas, which contrasted with the prevailing decreasing trend observed in the middle basin. Additionally, a small region within the lower basin displayed a decreasing trend (see Fig. 3.11). The trends observed in Maximum 7-Day Runoff (MAX7) and the 5th percentile runoff (Q5) displayed broadly similar patterns to those of MAR. However, when it comes to trends in low flow, specifically for Minimum 7-Day Runoff (MIN7) and the 95th percentile runoff (Q95), there were slight variations in spatial distribution compared to other hydrological indicators. Notably, more pronounced negative trends were evident in the middle and lower basin regions, albeit with relatively lower local variability.

Significant trends were observed mainly in regions that showed positive trends for annual runoff and high flow, particularly in the lower basin. In contrast, there was a significant negative trend for low flow and a less significant positive trend throughout the domain, which was particularly visible in the middle and lower basin. In addition to the differences in the significance tests, large differences were also observed in the model agreements for trend detection with respect to annual runoff, low flow, and high flow. For most of the region, the models consistently detected trends in

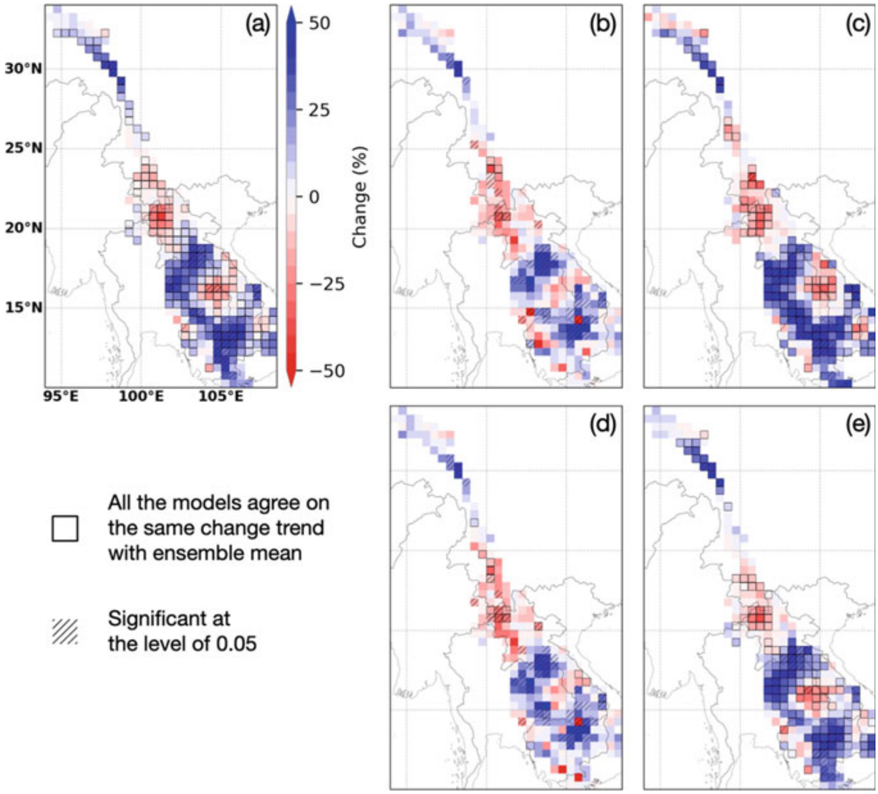

Fig. 3.11 Spatial distribution of change trends in **a** MAR, **b** MIN7, **c** MAX7, **d** Q95, and **e** Q5, based on the model ensemble mean

annual runoff and high flow, aligning with the trend direction indicated by the model ensemble mean. This alignment encompassed both positive and negative trends, with all models demonstrating the same directional consistency. However, for low flow, there were more noticeable inconsistencies between the model estimates of trends. Throughout the entire domain, the models only agreed in a few pixels (mostly with respect to a negative trend), while the disagreement among models for low flow trends was widespread across the upper and lower basin.

In addition to our multi-model analysis of runoff changes, we provide a summary from the literature regarding streamflow patterns. It was observed that, during the time span from 1960 to 2010, there existed a general downward trend in annual streamflow within the basin. However, after 2010, no clear trend was detectable, although the confidence level associated with such a trend was low, as indicated by Ruiz-Barradas and Nigam (2018). Most of the studies conducted on historical streamflow in the basin reported a decreasing trend, while a minority of studies indicated the opposite—an increasing trend in streamflow. These discrepancies in findings can be attributed to variations in data sources and methodologies employed in each study, as summarized in Table 3.3.

Studies have indicated that the drivers behind streamflow alterations vary across different regions and time periods. Climate change emerged as a primary catalyst for changes in streamflow within the Lancang-Mekong River Basin (LMRB) before 2010, whereas human activities, particularly dam construction, became more influential after 2010. Climate change predominantly governed alterations in annual streamflow during the transitional period from 1992 to 2009, accounting for 82.3% of the changes, while human activities contributed to 61.9% of the streamflow changes in the post-impact period from 2010 to 2014, as outlined by Li et al. (2017). When considering annual streamflow and water-level variations, the hydrological response within the Lancang River Basin is observed to be more sensitive to climate factors than to human activities, especially when compared to the Mekong River Basin (Li & He, 2008). This discrepancy underscores the escalating impact of intensive human activities on hydrological processes, particularly within the Mekong River Basin in recent years (Shin et al., 2020).

3.2.4 Historical Impacts of Dams on Streamflow

Streamflow in the Mekong River has been altered by dams, both in the mainstream and tributaries (Han et al., 2019; Pokhrel et al., 2018a; Räsänen et al., 2017; Shin et al., 2020). Specifically, upstream flow regulation by dams has resulted in reduced peak flow and increased low flow, attenuating the flood pulse amplitude. Such changes in streamflow patterns at various mainstem and tributary locations within the Mekong River Basin have been investigated by numerous studies using either observed streamflow records or basin-wide hydrological modelling. For example, Li et al. (2017) examined the observed streamflow at five gauging stations for the pre-development (1960–1991), transition (1992–2009), and post-development (2010–2014) periods and found that the dam filling and operation reduced streamflow in the upper portion of the basin, but such an impact was relatively small at the Stung Treng station in the downstream. Importantly, they reported that dam operations, especially the cascade dams in the Lancang River in China, reduced wet season flow and increased dry season flow resulting in a unique seasonal variation compared to the pre-development period. Numerous other studies have conducted similar analysis suggesting that the impact of upstream dams have already been felt in terms of alterations in streamflow signatures even in the mainstream Mekong (e.g., Campbell, 2007; Cochrane et al., 2014; Han et al., 2019; Räsänen et al., 2017; Zhao et al., 2012). These studies have used different statistical techniques to detect the changes in streamflow in a particular year or during a given period and attribute the change to dam construction. For example, the changes in streamflow during 2010–2014 period have been linked primarily to the construction of large dams (i.e., the Jinghong, Xiaowan, Gongguoqiao, and Nuozhadu) in the Lancang River by assuming that filling of new reservoirs with high storage capacity directly affected downstream flows (Li et al.,

Table 3.3 Changes in streamflow over the Lancang-Mekong River Basin and its upper (LRB) and lower (MRB) parts

References	Location	Data		Period	Annual streamflow	Seasonal streamflow	
		Variable/Model (source)	Observation			Dry season	Wet season
He and Chen (2002)	LRB	Discharge (MRC)	Yes	1962–2000	Increase in base flow	Substantial increase in flow	Discharge are reduced by 25%
Kummu and Varis (2007)	LRB	Water level and discharge (MRC)	Yes	1962–2000	Increase in mean flow in post-dam period (1993–2000) compared to pre-dam period (1962–1992)	N/A	N/A
Lu et al. (2008)	MRB	Water level and discharge (MRC)	Yes	1962–2003	Both the water level and baseflow are decreased	Minima flow increased	N/A
Kummu and Sarkkula (2008)	MRB	Water level and discharge (MRC)	Yes	1923–1965 1997–2006	Water level is decreased	Water level is increased	Flood peaks are reduced
Delgado et al. (2010)	LMRB	Discharge (Southern Institute of Water Resources Research in Ho Chi Minh City, Vietnam)	Yes	1913–2007	Flood magnitude is decreasing but the variability is increasing	N/A	Flood magnitude is decreasing but the variability is increasing
Piman et al. (2012)	LMRB	SWAT simulation	No	1987–2006	N/A	63% increase in dry season flows	22% decrease in wet season flows
Räsänen et al. (2012)	LMRB	VMod simulation	No	1990–2008	Not clearly determined	90% increase in December–May flows	A 20–22% decrease in June–November flow

(continued)

Table 3.3 (continued)

References	Location	Data		Period	Annual streamflow	Seasonal streamflow	
		Variable/Model (source)	Observation			Dry season	Wet season
Cochrane et al. (2014)	LMRB	Discharge (MRC)	Yes	1960–2010	Water levels are slowly decreased in downstream MRB	Mean water levels are increased for 30%	Mean water levels are increased for less than 5%
Räsänen et al. (2017)	LMRB	Discharge (MRC) and VMod simulation	Yes	1960–2014	N/A	Increased by 121–187% in LRB and increased in 41–74% in MRB	Increased by 32–46% in LMR and increased in 0–6% in MRB
Li et al. (2017)	LMRB	Discharge (MRC)	Yes	1960–2014	Streamflow is increased in the LRB, but no clear trend is found in the MRB, resulting a no significant change in the LMRB (less than 3%)	Increased by 23–55% in LRB and by 9–69% in MRB	Decreased by 10–32% in LMR and decreased by 0–13% in MRB
Hoang et al. (2019)	LMRB	VMod simulation forced by CMIP5 (RCP4.5 and RCP8.5)	No	2036–2065	No clear trend is determined	Sharply increased by 45–150%	Decreased by 0–25%
Kingston et al. (2011)	LMRB	SLURP model simulation	No	2 °C warming across seven GCMs	Mean monthly river discharge changes from −16 to +55%	Greatest increases in May and June	Greatest decreases are found in July and August

(continued)

Table 3.3 (continued)

References	Location	Data		Period	Annual streamflow	Seasonal streamflow	
		Variable/Model (source)	Observation			Dry season	Wet season
Eastham et al. (2008)	LMRB	Hydrological simulation based on 11 GCMS	No	1951–2030	Increased by 21% with a range from −8 to 90%	N/A	N/A
Västilä et al. (2010)	LMRB	VIC simulation	No	1995–2004 2010–2049	Only a 4% increase in annual streamflow	Decreased	Increased by 5%

2017). Such effects of Lancang cascade dams have been felt the most in the immediate downstream regions; the effects tend to decrease downstream because of larger flow accumulation from the tributaries and relatively small storage compared to the high flow volume in the far downstream.

The observation-based studies have provided crucial insights into the changes in streamflow and its seasonal signatures. However, it is challenging to attribute the recorded changes explicitly to climate variability or dam construction by using only observational data. Hydrological modelling can fill this gap by providing a framework where simulations can be conducted with and without considering dams—given the same climate conditions—such that the direct impacts of dams can be estimated by using the difference between two such simulations. However, very limited such studies have been conducted to date because of the challenges in simulating the complex and interconnected river-floodplain-reservoir processes over the entire basin. Among few such studies is that by Shin et al. (2020) that used a newly developed, high-resolution (~5 km grid) hydrodynamic model called the CaMa-Flood-Dam to explicitly simulate the effects of climate variability and dams over the entire Mekong basin. The model is based on the global hydrodynamics model CaMa-Flood (Yamazaki et al., 2014) and a new reservoir inundation and release scheme (Shin et al., 2019).

The study found that the impact of dams significantly increased after 2010 because the basin-wide reservoir storage capacity doubled from 2010 to recent years. In particular, river flows at various mainstem locations in the middle and lower reaches have been increasingly altered by dams in recent years (Fig. 3.12). This rapid increase in storage capacity came primarily from the completion of the Lancang cascade dams (Hecht et al., 2019; Pokhrel et al., 2018a). The study by Shin et al. (2020) also explicitly simulated water levels across the basin and inundation both the upstream and downstream of dams. Consistent with the changes in streamflow, the study reported a noticeable change in water levels downstream of dams, primarily after 2010 (Fig. 3.13). Their model explicitly simulated inundation dynamics in the natural rivers and floodplains as well as the upstream of dams. The model realistically captured the flood occurrence behind the major dams across the basin (Figs. 3.14 and 3.15) that depicted the influence of dam regulation at different levels on the flood besides climate change. Another study analysed the changes in streamflow due to climate change and dams by combining a hydrological model and observed discharges (Han et al., 2019); however, their model did not explicitly simulate reservoir operation. They quantified the impact of climate change and dams, reporting that during the 1987–2014 period the mean annual streamflow declined by ~ 6% compared to the 1980–1986 period. During the 1987–2007 period, only 43% of these changes were attributed to dams (~57% to climate change), but the contribution of dams rose drastically to 95% during the 2008–2014 period.

These findings suggest that the impacts of dams on streamflow were rather small until the late 2000s but have substantially increased in recent times since the completion of cascade dams in the Lancang river. Indeed, the total basin-wide active dam storage before 2010 amounts to only about 2% of the mean annual flow volume (Hecht et al., 2019), which increased rapidly after 2010 (Shin et al., 2020) and is

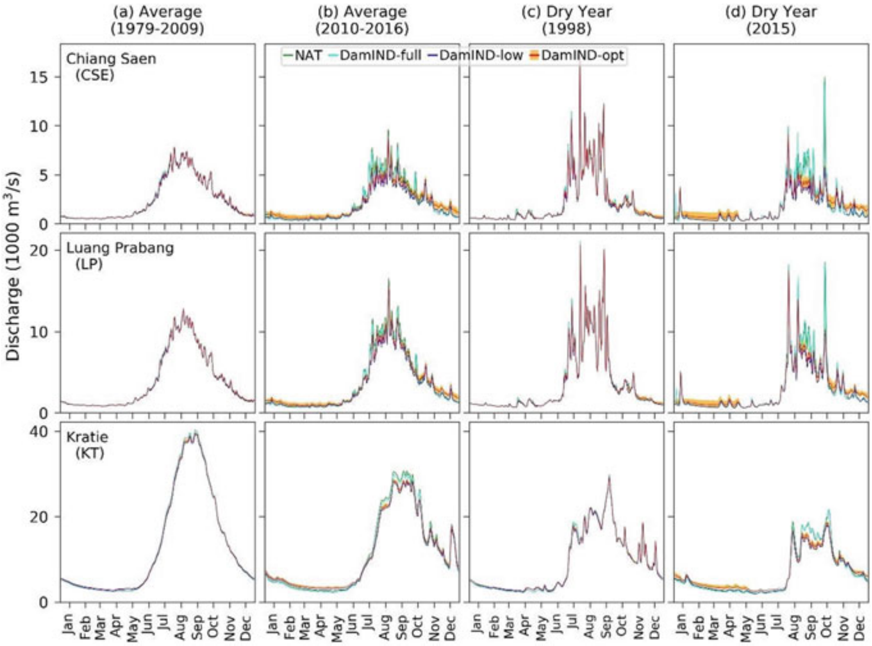

Fig. 3.12 River discharge simulated by CaMa-Flood-Dam model for three selected stations in the mainstem Mekong. Seasonal average for the periods of **a** 1979–2009 and **b** 2010–2016, and two dry years **c** before and **d** after basin-wide reservoir storage capacity doubled in 2010. NAT, DamIND-full, DamIND-low, and DamIND-opt denote simulations without dams (i.e., natural setting), considering dams with reservoirs at full level, considering dams with reservoirs at low level, and considering dams with reservoirs at the optimised regulation level, respectively. Figure modified after Shin et al. (2020)

expected to rise further to about 19% of annual mean flow volume by the mid-2020s (Hecht et al., 2019). This increase is expected to come not only from the continued dam construction in the Lancang river but also from the construction of several large dams in the lower basin including the recently completed Xayabouri Dam (Stone, 2011, 2016) and controversial Luang Prabang dam that is under construction (Fumagalli, 2020). Dam construction in the Laos and Cambodia portions of the Mekong Basin remains a highly contested issue and whether and how many of the proposed dams will be constructed in the coming decades remains highly uncertain. However, hydrological and hydrodynamic simulations clearly suggest that the fear of killing the Mekong by altering the magnitude, timing and duration of the Mekong flood pulse is a reality if many of the dams were to be built (Pokhrel et al., 2018b). If the mainstream flow were to be regulated by upstream dams, the hydrology of the Tonle Sap Lake—including the flow reversal in the Tonle Sap River—could be largely disrupted, also bringing major changes in flood dynamics in the Mekong Delta (Pokhrel et al., 2018b) and directly impacting fisheries across the Lower Mekong, especially in the Tonle Sap Lake region (Burbano et al., 2020). Some approaches have

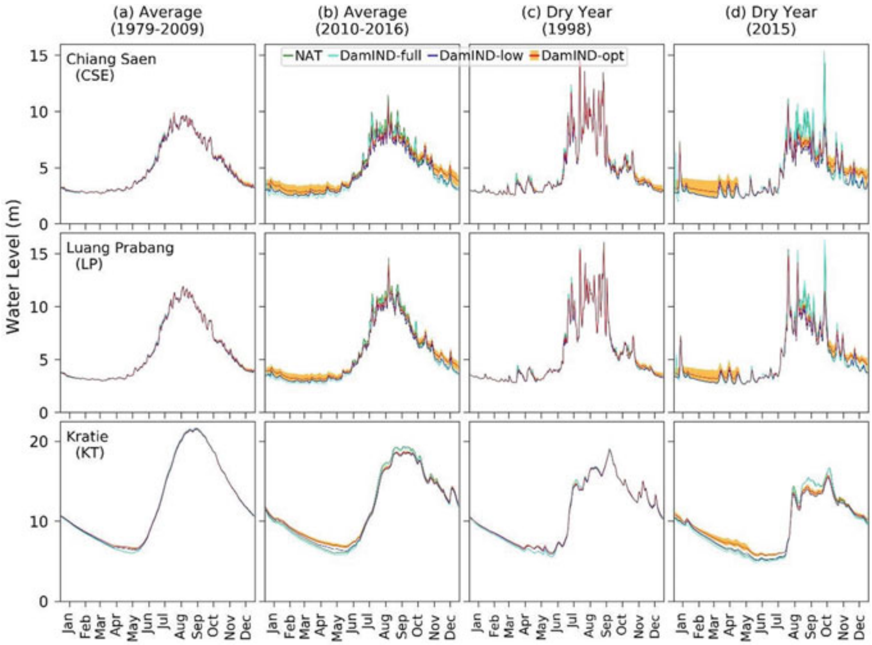

Fig. 3.13 Same as in Fig. 3.12 but for water level

been suggested to minimise downstream impacts, especially on fisheries (Sabo et al., 2017), but the practical aspects of such engineering approaches remain unexplored (Williams, 2018).

3.2.5 Projected Changes in Streamflow

Unlike historical streamflow changes, previous studies have consistently projected an increasing trend in streamflow within the Lancang-Mekong River Basin (LMRB), regardless of the climate forcings and models employed. However, it is important to note that the flow regime in this basin is highly susceptible to various drivers, including dam construction, irrigation expansion, land-use changes, and climate change. Substantial changes are anticipated in both annual and seasonal flow patterns, with an overall increasing trend (Hecht et al., 2019; Hoang et al., 2019). Notably, hydropower development, while exerting a limited influence on total annual flow, has the most significant seasonal impact on streamflow, leading to an increase in the dry season and a decrease in the wet season, surpassing the effects of other drivers (Hoang et al., 2019). Furthermore, studies suggest that climate change may lead to a 15% increase in annual streamflow, while irrigation expansions could result in a slight decrease of 3% in annual streamflow over the period from 2036 to 2065 compared to

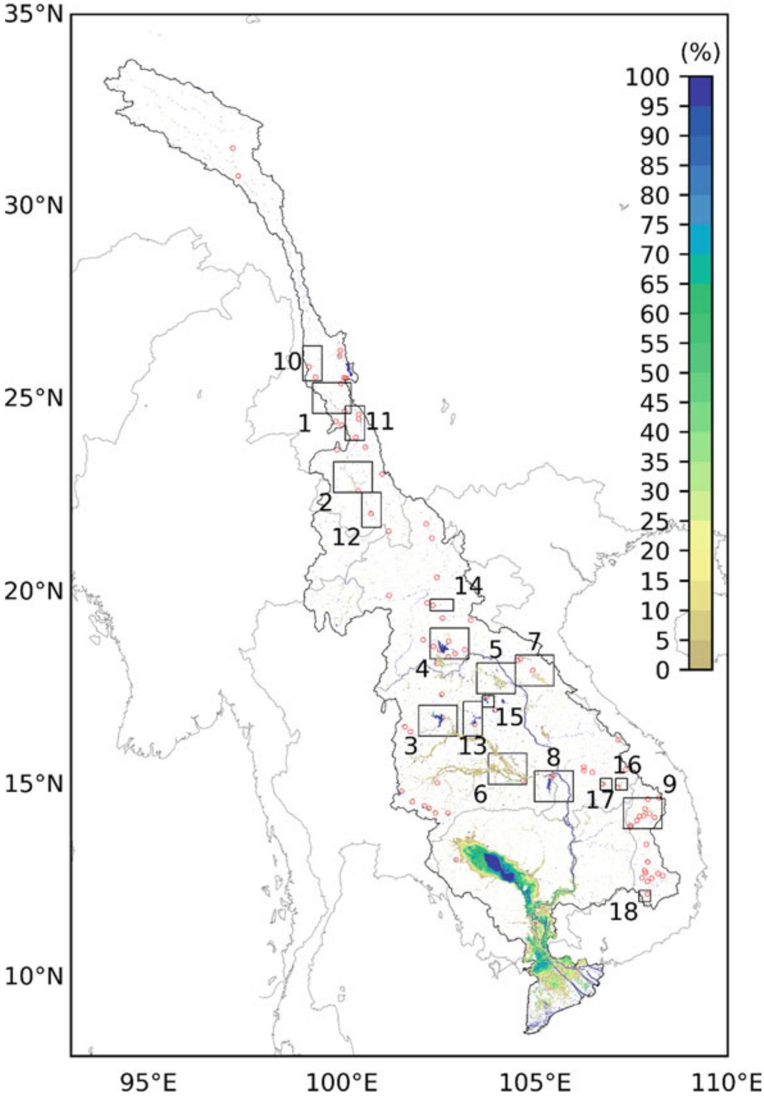

Fig. 3.14 Simulated flood occurrence at 3-arcsec (~90 m) resolution for the entire MRB (Shin et al., 2020). Labeled black boxes indicate regions for which a zoomed-in view is presented in Fig. 3.15. Red circles indicate the locations of dams simulated in the CaMa-Flood-Dam model

the period from 1971 to 2000. These projections were based on statistically downscaled data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and utilized a distributed hydrological model, VMod, with a spatial resolution of 5 km × 5 km (Hoang et al., 2019). Taking future dam development into account, the change ratio in the dry season (70% increase) surpasses that in the wet season (15% decrease).

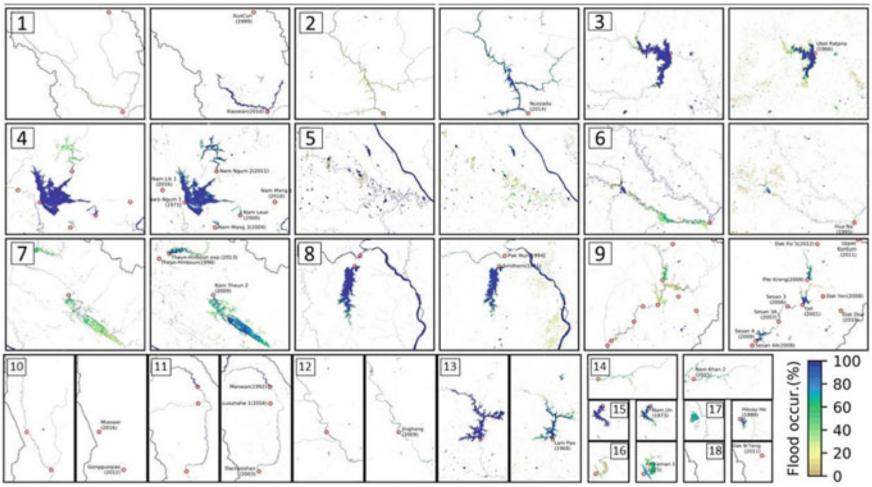

Fig. 3.15 Comparison of inundation dynamics simulated by CaMa-Flood-Dam model (left; 1979–2016 period) with the Global Surface Water (GWS) data (right; Pekel et al. (2016); 1984–2018 period). Results are shown as flood occurrence for the regions indicated in Fig. 3.14. Red circles indicate dam locations. Figure modified after Shin et al. (2020)

In the 3S tributary, streamflow is projected to increase by 96% in the dry season and decrease by 25% in the wet season, highlighting higher streamflow sensitivity to climate change and human activities in the 3S system compared to the entire LMRB (Shrestha et al., 2016).

It is important to note that scenarios for streamflow changes exhibit spatial variability, especially within the Mekong River Basin (Liu et al., 2022). While an increasing streamflow trend is projected for the future of LMRB, uncertainties remain substantial. For instance, studies have reported varying projections, including an annual runoff increase ranging from 4 to 90% by the 2030s compared to the historical period (1951–2000), based on different global climate models (GCMs) (Eastham et al., 2008). Other studies, using CMIP5 datasets for the near future (2036–2065), have reported relatively modest changes in mean annual flow, ranging from 3 to 10% in the LMRB (Phi Hoang et al., 2016; Västilä et al., 2010).

Furthermore, projections indicate that the magnitude and frequency of extreme high-flow events are expected to increase, while low-flow events are anticipated to become less frequent, primarily due to the impacts of climate change (Phi Hoang et al., 2016). This shift could potentially heighten flood risks within the basin. However, it's worth noting that the massive construction of hydropower facilities, which has altered discharge patterns, is expected to exert a more substantial influence on hydrography in the next few decades compared to climate change (Lauri et al., 2012). Additionally, different patterns of hydrological changes may be observed in different subbasins of the basin, and the expected change ratios vary by location (Phi Hoang et al., 2016). Moreover, the number of wet days is projected to increase by the end of the twenty-first century (2080–2099), potentially increasing flood risk while benefiting water utilization during dry periods (Kiem et al., 2008).

3.2.6 Uncertainties in Streamflow Simulation

Due to the constraints of time and cost associated with large-scale and long-term field observations, hydrological models (HMs) and land surface models (LSMs) are valuable tools for simulating and managing water resources. Uncertainties in a hydrological simulation are inevitable due to the difference between the natural hydrological processes and model descriptions. Thus, uncertainties must be considered to reflect the reliability of models.

To assess uncertainties in model simulation in the Lancang-Mekong River Basin, observed discharge data from seven hydrological stations were used to evaluate ten HMs and LSMs from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP2a). The simulated discharge data forced by Global Soil Wetness Project 3 (GSWP3) data in the ISI-MIP2a simulation round were selected. To capture the diverse aspects of hydrological regimes and their associated uncertainties, we considered simulated discharge series at various percentiles, including the 5th percentile (Q5), 25th percentile (Q25), 50th percentile (Q50), 75th percentile (Q75), and 95th percentile (Q95). These percentiles provide insights into extremely low discharge (Q5), the median discharge (Q50), high flow conditions (Q95), and additional discharge information in the form of Q25 and Q75, contributing to a comprehensive evaluation of the uncertainties inherent in different hydrological scenarios (Fig. 3.16; Table 3.4).

For Q5 (Fig. 3.17), large deviations occurred between the simulated and observed discharge series. Discharge curves simulated by different models were more divergent than that of high flow (Fig. 3.18). The model ensemble discharge and the observed discharge displayed high consistency at most stations for all percentiles. Systematic errors occurred at Q5 for CLM4, H08 and LPJmL, where these models simulated a much smaller discharge than the observed and other models. As for high discharge percentiles, the simulated curves were more concentrated, which indicated more realistic simulations and smaller uncertainties.

Dispersion of the simulated discharge series reflects the uncertainties in discharge simulations among different models. The large deviations between the selected models indicated that uncertainties in discharge simulation for lower percentiles were much greater than that for higher percentiles.

The analysis of statistical metrics consistently revealed a pattern of decreasing model uncertainty as we moved from lower percentiles to higher percentiles (Fig. 3.19). Furthermore, all the models exhibited significant correlations with the observed discharge series, with most models achieving an R-squared (R2) value greater than 0.60 for all stations. Notably, several models surpassed an R2 value of 0.80 for stations located downstream of the river, including WaterGAP2, MPI-HM, H08, MATRISO, and WAYS (Table 3.5). These results signify that the simulated discharge series produced by all the models satisfactorily replicate the observed

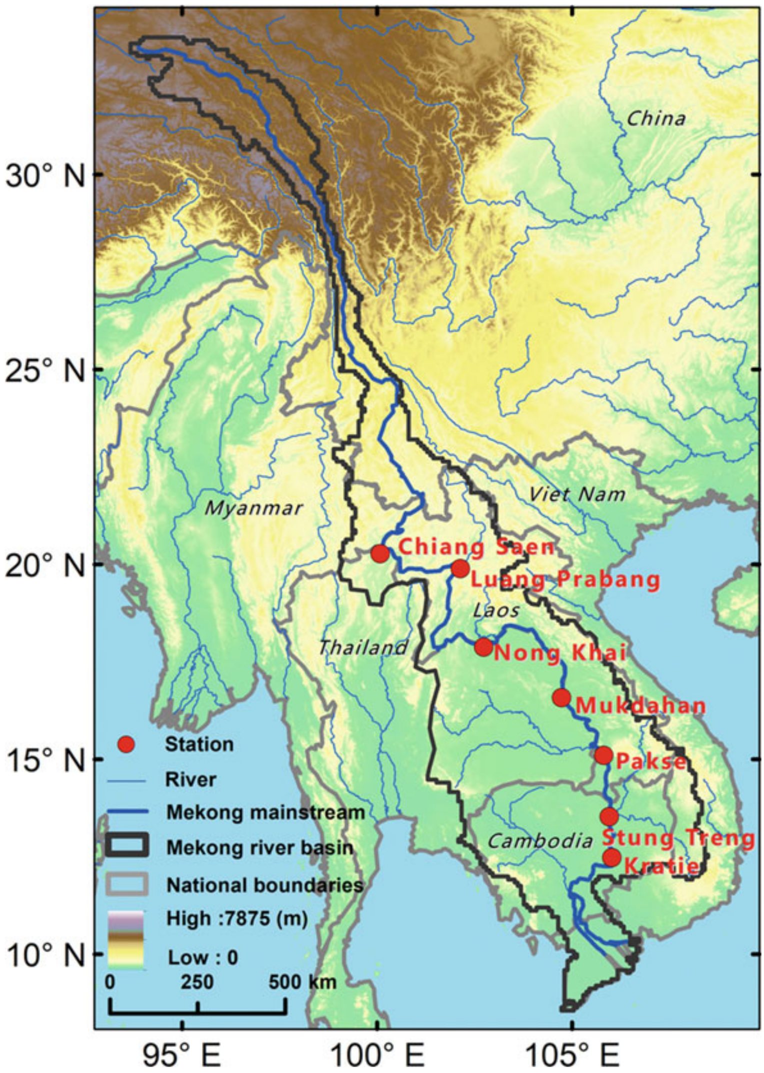

Fig. 3.16 Location of the seven hydrological stations

series. In contrast to the single model series, the model ensemble series consistently outperformed at all stations. Generally, R2 values tended to increase as we moved closer to the river's estuary but exhibited a decline for stations in proximity to the estuary, such as Stung Treng and Kratie. Figure 3.19b demonstrated that the majority of Nash–Sutcliffe Efficiency (NSE) values exceeded 0.40, indicating that the model simulations could be considered reliable. Similar to R2, the model ensemble displayed higher NSE values than the individual models at most stations. WaterGAP2 emerged as the top-performing model across all stations based on NSE

Table 3.4 General information of the ten evaluated Global Hydrological Models (GHMs) and Land Surface Models (LSMs)

Model	Class of model	Spatial resolution (°)	Evapotranspiration	Dam/Reservoir	Surface runoff	Routing
CLM4	LSM	0.5	The mass transfer equation	No	TOPMODEL-based (Beven & Kirkby, 1979)	Linear reservoir, constant flow velocity
DBH	GHM	0.5	Energy balance	No	SiB2 model based (Sellers et al., 1986)	Linear reservoir model
H08	GHM	0.5	Bulk approach	Yes	An improved bucket model (Hanasaki et al., 2008)	Based on DDM30
LPJmL	GHM	0.5	Priestley–Taylor	Yes	A semi-empirical method (Haxeltine & Prentice, 1996)	Continuity equation derived from linear reservoir model, routing data according to DDM30
MATSIRO	LSM	0.5	Penman–Monteith	Yes	SiB2 model based (Sellers et al., 1986)	TRIP model based on DDM30
MPI-HM	GHM	0.5	Bulk approach	No	HD-Model based (Hagemann & Dümenil, 1998)	Linear reservoir cascade based on DDM30
ORCHIDEE	LSM	0.5	Bulk approach	No	A multi-layer soil hydrology scheme (de Rosnay et al., 2002)	STN-30p river network
WaterGAP2	GHM	0.5	Priestley–Taylor	Yes	HBV model based (Alcamo et al., 2003)	Linear reservoir, flow velocity based on Manning–Strickler based on DDM30
WAYS	GHM	0.5	Penman–Monteith	No	Xinanjiang model based (Zhao, 1992)	CaMa-Flood

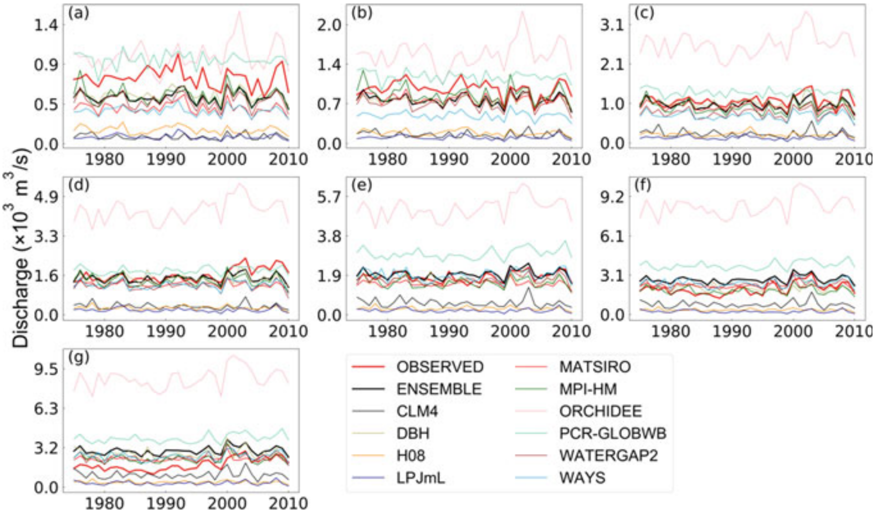

Fig. 3.17 Comparison of the annual discharge series of observed and simulated discharges at the 5th percentile. **a** Chiang Saen, **b** Luang Prabang, **c** Nong Khai, **d** Mukdahan, **e** Pakse, **f** Stung Treng, and **g** Kratie

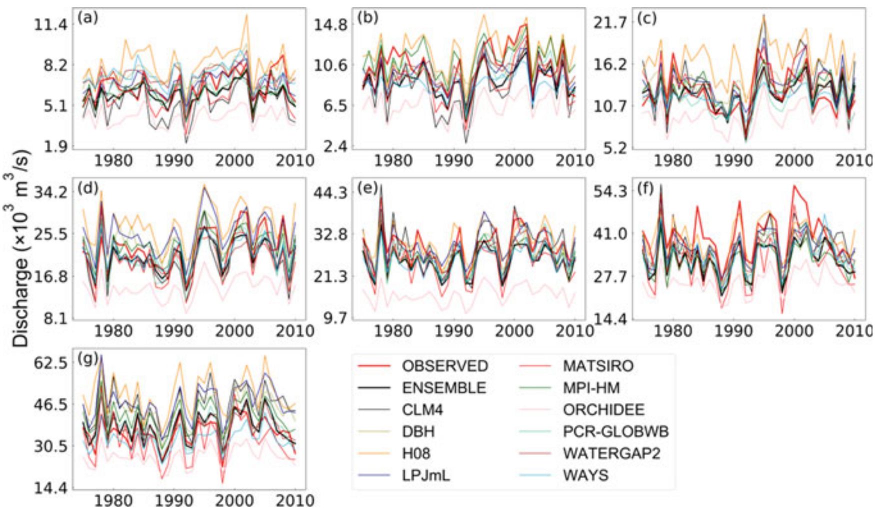

Fig. 3.18 Comparison of the annual discharge series of observed and simulated discharges at the 95th percentile. **a** Chiang Saen, **b** Luang Prabang, **c** Nong Khai, **d** Mukdahan, **e** Pakse, **f** Stung Treng, and **g** Kratie

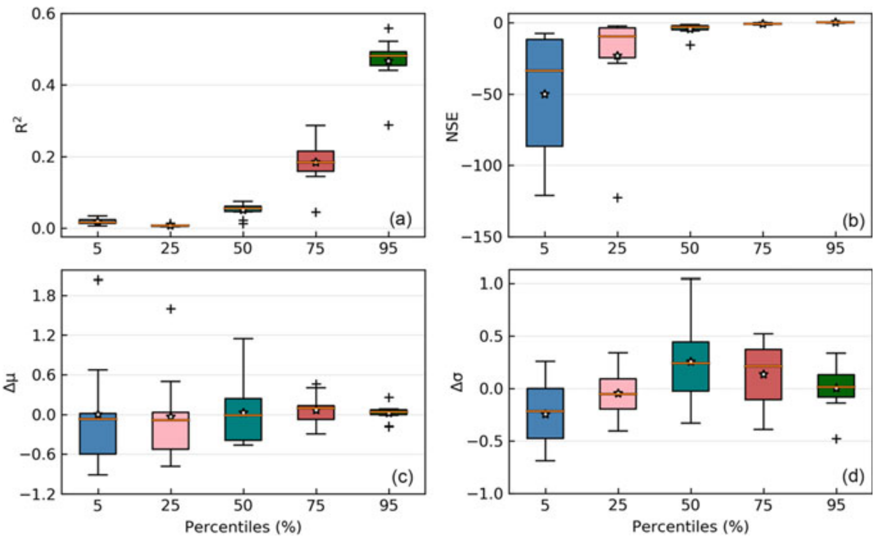

Fig. 3.19 Comparison of model performances with different metrics at different percentiles. **a** R2, **b** NSE, **c** Δμ, and **d** Δσ. Details of the definition of metrics could be found in Chen et al. (2021a, 2021b)

and even outperformed the model ensemble at stations in Luang Prabang, Pakse, and Kratie. Additionally, Δμ represented negative deviations at Chiang Saen and Luang Prabang stations, while positive deviations were observed at Nang Khai and Kratie stations for most of the models. Δσ indicated deviations from the standard deviation between the simulated discharge series and the observed data. Notably, H08 and ORCHIDEE exhibited significantly different Δσ values compared to other models. H08 displayed larger Δσ values than the other models at all stations, while ORCHIDEE demonstrated the opposite performance. The DBH model exhibited a substantial positive deviation in Δμ but performed well in Δσ.

In terms of model performance rankings based on the scoring system, WaterGAP2 secured the top position, followed by WAYS, PCR-GLOWBW, MPI-HM, and MATRISO, which ranked 2nd, 3rd, 4th, and 5th, respectively. On the other hand, ORCHIDEE received the lowest ranking, primarily due to its poor performance in Δμ. The CLM4 model exhibited less favorable performance, particularly in terms of Nash–Sutcliffe Efficiency (NSE), with values of 0.18 at Chiang Saen and 0.24 at Kratie. Additionally, the CLM4 model displayed negative deviations for Δμ at Chiang Saen (−0.46) and Luang Prabang (−0.39). These results indicated that the simulated discharge series for the CLM4 model diverged significantly from the outcomes of other models. As we moved closer to the estuary, both NSE and R2 values for most models approached 1, indicating improved model performance. However, there was a decline in these values at the Kratie station. Furthermore, negative Δμ values were observed for most models at Chiang Saen, Luang Prabang, and Pakse, suggesting that these models consistently underestimated the magnitude of

Table 3.5 Model performances at seven hydrological stations based on the Nash–Sutcliffe efficiency coefficient (NSE), correlation coefficient (R2), mean deviation in mean (Δμ), and mean deviation in standard deviation (Δσ). Details of the rank system could be found in Chen et al. (2021a, 2021b)

Station	Indicator	CLM4	DBH	H08	LPJmL	MATRISO	MPI-HM	ORCHIDEE	PCR-GLOWBW	WaterGAP2	WAYS	ENSEMBLE
Chiang Saen	NSE	0.18	0.45	0.52	0.54	0.60	0.71	0.50	0.55	0.71	0.25	0.79
	R^2	0.52	0.64	0.75	0.65	0.72	0.73	0.65	0.57	0.79	0.49	0.80
	Δμ	−0.46	0.17	−0.02	−0.11	−0.26	−0.10	−0.21	−0.02	0.08	−0.04	−0.10
	Δσ	−0.18	0.17	0.35	0.12	−0.06	−0.07	−0.48	−0.11	0.16	0.18	−0.09
Luang Prabang	NSE	0.39	0.56	0.69	0.65	0.73	0.75	0.57	0.69	0.85	0.59	0.84
	R^2	0.60	0.61	0.80	0.70	0.78	0.80	0.72	0.71	0.85	0.64	0.85
	Δμ	−0.39	0.08	−0.05	−0.14	−0.20	0.10	−0.18	−0.01	−0.01	−0.19	−0.10
	Δσ	−0.14	−0.01	0.22	0.01	−0.11	0.11	−0.48	0.00	−0.03	−0.13	−0.13
Nang Khai	NSE	0.60	0.45	0.50	0.65	0.75	0.71	0.66	0.73	0.86	0.71	0.86
	R^2	0.72	0.65	0.81	0.77	0.80	0.76	0.73	0.73	0.86	0.73	0.87
	Δμ	−0.08	0.29	0.16	0.05	0.02	0.09	0.08	−0.03	0.02	0.02	0.06
	Δσ	0.19	0.11	0.42	0.21	0.13	0.09	−0.40	−0.07	−0.02	0.01	0.00
Mukdahan	NSE	0.72	0.67	0.73	0.73	0.82	0.74	0.57	0.74	0.90	0.89	0.91
	R^2	0.77	0.78	0.88	0.82	0.85	0.78	0.69	0.75	0.90	0.89	0.91
	Δμ	−0.19	0.26	0.17	0.07	−0.17	0.12	0.00	−0.06	−0.03	0.04	0.02
	Δσ	−0.04	0.08	0.28	0.20	−0.10	0.04	−0.52	−0.06	−0.09	−0.04	−0.08
Pakse	NSE	0.63	0.81	0.85	0.82	0.79	0.78	0.48	0.75	0.91	0.90	0.90
	R^2	0.68	0.82	0.88	0.85	0.83	0.78	0.65	0.76	0.92	0.90	0.92
	Δμ	−0.08	0.12	0.02	−0.04	−0.19	−0.02	−0.10	0.06	−0.01	0.00	−0.02
	Δσ	0.03	−0.04	0.10	0.06	−0.12	−0.10	−0.60	−0.06	−0.12	−0.14	−0.15
Stung Treng	NSE	0.60	0.82	0.82	0.83	0.74	0.73	0.51	0.73	0.87	0.87	0.88

(continued)

Table 3.5 (continued)

Station	Indicator	CLM4	DBH	H08	LPJmL	MATRISO	MPI-HM	ORCHIDEE	PCR-GLOWBW	WaterGAP2	WAYS	ENSEMBLE
	R^2	0.64	0.83	0.84	0.84	0.78	0.74	0.62	0.73	0.88	0.88	0.90
	$\Delta\mu$	−0.11	0.07	−0.02	−0.08	−0.19	−0.09	0.11	0.02	0.04	0.02	−0.02
	$\Delta\sigma$	−0.06	−0.11	0.03	−0.03	−0.19	−0.19	−0.53	−0.13	−0.11	−0.16	−0.21
Kratie	NSE	0.24	0.52	0.47	0.57	0.77	0.60	0.51	0.70	0.87	0.89	0.86
	R^2	0.56	0.84	0.86	0.84	0.78	0.76	0.64	0.74	0.90	0.90	0.91
	$\Delta\mu$	0.21	0.48	0.35	0.27	−0.11	0.28	0.22	0.16	0.15	0.09	0.21
	$\Delta\sigma$	0.28	0.21	0.44	0.37	−0.11	0.16	−0.48	0.01	0.00	−0.12	0.00
	RANK	9	8	7	6	5	4	10	3	1	2	

discharge series at these stations. Nevertheless, as the stations moved closer to the estuary, models with negative $\Delta\mu$ values decreased in number, and only two models (MATRISO and ORCHIDEE) displayed negative values for $\Delta\mu$ at the Kratie station. This shift underscores the enhancement in model performances as we moved closer to the estuary.

The models had poor performances for low discharge percentiles, although the simulated performances improved as discharge percentiles increased. The model performances in terms of discharge simulations generally improved with the distance to the estuary for all discharge percentiles. For the Lancang-Mekong River Basin, the discharge increases from upstream to downstream, which can partly explain the better performance downstream. However, the models had difficulties in simulating discharge for the river sections close to the estuary. The complex processes between the freshwater and saline water bodies may be the cause of this difficulty. The results suggest that current models have limits in extreme hydrological event simulations, which is vital for water resources management. It also indicates that current models are limited in extreme hydrology event prediction, which usually brings huge losses to the economy and society.

3.3 Baseflow Estimation and Change in the Basin

Streamflow in a river consists of two components, namely baseflow and stormflow. Baseflow refers to the component of streamflow originating from groundwater storage and other delayed sources (Hall, 1968). It represents the flow within a stream that would persist even in the absence of direct runoff resulting from rainfall. As a result, baseflow is an important source of water for a river, especially in dry seasons. Baseflow estimation has been achieved through isotopic and chemical tracer methods (Genereux, 1998; Muñoz-Villers et al., 2016). However, these tracer methods are often costly and labor-intensive when applied in field measurements (Lott & Stewart, 2016). To address these challenges, various mathematical methods have been developed for baseflow estimation that do not require the use of tracers. These methods include graphical approaches (Institute of Hydrology, 1980; Sloto, 1996) and digital filter methods (Anand Tularam & Ilahee, 2008; Chapman, 1991; Eckhardt, 2005; Furey & Gupta, 2001; Huyck et al., 2005; Lin et al., 2007; Maxwell, 1996). These techniques provide alternative means of estimating baseflow efficiently and cost-effectively (Fig. 3.20).

In this chapter, the baseflow of two typical hydrologic stations in the Mekong River Basin, namely Yongjinghong and Kratie, were estimated and projected using mathematical methods. The Yongjinghong Station is located in the Upper Mekong River Basin, and the Kratie Station is located in the Lower Lancang-Mekong River Basin.

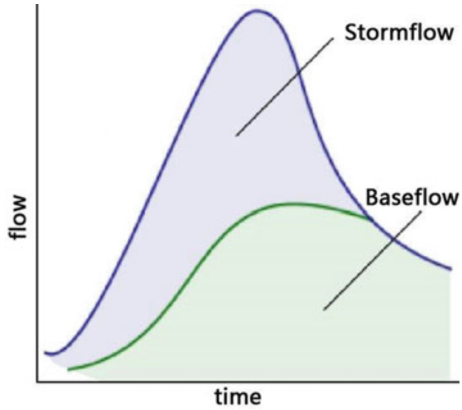

Fig. 3.20 Schematic diagram of baseflow. Total streamflow in a river consists of two components, namely baseflow and stormflow

3.3.1 Comparison of Baseflow Estimation Methods

3.3.1.1 Baseflow Evaluation Criterion

Because of the lack of baseflow observation data, it is difficult to evaluate the accuracy of different baseflow separation methods through the observed baseflow. In this chapter, a robust mathematical evaluation method is employed to evaluate the accuracy of different separation methods. The main guideline is as follows. When the quick flow (interflow and overland flow) of a basin ceases on a certain day, the streamflow is completely replenished by the baseflow, and the streamflow of that day is equal to the baseflow. The daily streamflows of these days can then be used as the baseflow benchmark to assess different baseflow separation methods. According to Brutsaert (2008), days when streamflow is completely replenished by baseflow (hereafter baseflow days) can be selected through the following four steps:

(1) Exclude days with streamflow $\frac{dy}{dt} \geq 0$, where $\frac{dy_i}{dt} = \frac{y_{i+1} - y_{i-1}}{2}$.
(2) Exclude two days before and three days after the day with streamflow $\frac{dy}{dt} \geq 0$.
(3) Exclude five days after high flow events that were identified by flood peaks greater than the 90th quantile of all daily streamflow observations (Cheng et al., 2016).
(4) Exclude days followed by a day with smaller $\frac{dy}{dt}$, namely $\frac{d^2y}{dx^2} < 0$.

These four steps have two purposes. The first three steps are to exclude the days when the streamflow may contain quick flow. The last step is to exclude the days when daily streamflow violates the pattern of baseflow recession during dry periods, namely followed by a larger $-\frac{dy}{dt}$ (Xie et al., 2020). Baseflow days selected by the four steps are shown in Fig. 3.21.

The baseflow days (Black points in Fig. 3.21) were used as the baseflow benchmark to evaluate the accuracy of different baseflow separation methods, based on the evaluation metrics of Kling-Gupta Efficiency (*KGE*) (Knoben et al., 2019) and relative bias (*BIAS*):

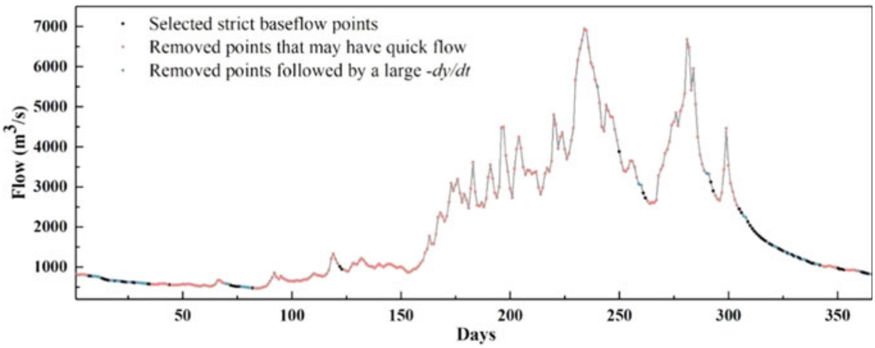

Fig. 3.21 Selecting baseflow days according to the four steps. The red points are excluded through the first three steps. The blue points are excluded through the last step. The daily streamflow observations are from the Yongjinghong station in 1980

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_m}{\sigma_o} - 1\right)^2 + \left(\frac{\underline{Q_m}}{\underline{Q_0}} - 1\right)^2} \tag{3.1}$$

$$BIAS = \frac{\sum_1^n (Q_{oi} - Q_{mi})}{\sum_1^n Q_{oi}} \tag{3.2}$$

where $\boldsymbol{r}$ is Pearson's correlation between the selected baseflow and the corresponding estimated baseflow. σ_o is the standard deviation of the selected baseflow, and σ_m is the standard deviation of the corresponding estimated baseflow. $\underline{Q_0}$ is the mean value of the selected baseflow, and $\underline{Q_m}$ is the mean value of the corresponding estimated baseflow. $\boldsymbol{Q_{oi}}$ and $\boldsymbol{Q_{mi}}$ are the selected baseflow and the corresponding estimated baseflow on the ith day, respectively.

3.3.1.2 Baseflow Separation Methods

In this chapter, 9 baseflow separation methods were evaluated, including 5 digital filter methods, namely the Chapman method, the LH method, the Eckhardt method, the EWMA method and the CM method, and 4 graphic methods, namely the UKIH method and three HYSEP methods. The digital filter methods are grounded on the assumption that baseflow constitutes the low-frequency component of streamflow, which exhibits a slow response to precipitation events, while quick flow represents the high-frequency component, reacting rapidly to precipitation. In contrast, the graphic methods identify specific low-flow points within a streamflow hydrograph, connect these points to form a continuous baseflow line, and subsequently constrain this baseflow line beneath the streamflow hydrograph to derive the baseflow hydrograph. For a more comprehensive understanding of these methods, their principles and specific details are presented in Table 3.6.

Table 3.6 The principles and details of 9 baseflow separation methods

	Method	Introduction	References
Graphic method	UKIH method	Turning points are selected as follows: (1) The streamflow series was divided into 5-day blocks without overlapping. The minimum streamflow of each block was denoted as $Q_1, Q_2, \ldots, Q_t$ (2) Every three minimum points were taken as a group, namely (Q_1, Q_2, Q_3), (Q_4, Q_5, Q_6), …, (Q_{t-1}, Q_t, Q_{t+1}), (3) Groups with $Q_t \leq 1.11Q_{t-1}$ and $Q_t \leq 1.11Q_{t+1}$ were selected. The central values are turning points Turning points are linearly interpolated as a baseflow line	Institute of Hydrology (1980)
	HYSEP-fixed HYSEP-slide HYSEP- Local	HYSEP had three algorithms to select low-flow points, namely fixed interval, sliding interval, and local minimum. The local minimum method is used to introduce HYSEP (1) The movement duration of overland flow was estimated by empirical relationship $\boldsymbol{N} = \boldsymbol{A}^{0.2}$, where $\boldsymbol{N}$ is the number of days when overland flow will cease, and $\boldsymbol{A}$ is the basin area (2) The entire period of streamflow is traversed with a sliding window, whose interval is equal to the odd integer nearest to $2N$. The lowest streamflow in the window was selected as the local minimum point (3) These local minimum points are connected to define the baseflow hydrograph	Sloto (1996)
Digital filter method	LH method	$f_k = \beta f_{k-1} + \frac{1+\beta}{2}(y_k - y_{k-1})(f_k \geq 0)$ $b_k = y_k - f_k$ where f_k indicates the kth quick flow filtered, y_k is the sum of kth baseflow and quick flow, and β is the filter parameter, assigned a value of 0.925 (Nathan & McMahon, 1990)	Lyne and Hollick (1979)
	Chapman method	$b_k = \alpha b_{k-1} + \frac{1-\alpha}{2}(f_k + f_{k-1})(0 \leq b_k \leq y_k)$ where the filter parameter α is recession constant and α can be calculated by recession analysis (Eckhardt, 2008)	Chapman (1991)
	CM method	$b_k = \frac{\alpha}{2-\alpha} b_{k-1} + \frac{1-\alpha}{2-\alpha} y_k (0 \leq b_k \leq y_k)$ where α is a recession constant calculated by recession analysis (Eckhardt, 2008)	Maxwell (1996)

(continued)

Table 3.6 (continued)

	Method	Introduction	References
	Eckhardt method	$b_k = \frac{(1-BFI_{max})\alpha b_{k-1}+(1-\alpha)BFI_{max}y_k}{1-\alpha BFI_{max}}$ where α is the recession constant, BFI_{max} is calculated by a backward filter method (Collischonn & Fan, 2013)	Eckhardt (2005)
	EWMA method	$b_k = \varepsilon y_k + (1-\varepsilon)b_{k-1}(0 \le b_k \le y_k)$ where ε is the smoothing constant, assigned a value of 0.013	Anand Tularam and Ilahee (2008)

3.3.1.3 Comparisons of Baseflow Separation Methods

Reservoir construction has significantly affected streamflow observations in the Lancang-Mekong River Basin since 2008. Thus, 2007 was selected as the last year of the baseflow separation in this study. Daily streamflow observations for the two hydrologic stations, namely Yongjinghong and Kratie, from 1980 to 2007 were obtained from the Mekong River Commission (https://portal.mrcmekong.org/home).

To evaluate the accuracy of the 9 baseflow separation methods, the baseflow points obtained through the four steps in Sect. 3.3.1.1 and the baseflow estimated using the 9 methods introduced in Sect. 3.3.1.2 were compared in the two hydrologic stations. Table 3.7 shows the evaluation result of the 9 baseflow separation methods for the two hydrologic stations. For Yongjinghong Station, the Eckhardt method has the largest value of KGE and the smallest value of BIAS among the 9 methods, with values of 0.86 and 5.98% respectively. For Kratie Station, the Eckhardt method also has the largest value of KGE and the smallest value of BIAS among the 9 methods, with values of 0.93 and 5.81% respectively. Generally, the Eckhardt method has the best performance to estimate baseflow for the two hydrologic stations. The good performance indicates that it is reliable to use the Eckhardt method in estimating baseflow for the two hydrologic stations in the LMRB.

3.3.2 Baseflow Estimation in the Basin

Using the Eckhardt method, the baseflows of the two hydrologic stations from 1980 to 2007 were estimated. From 1980 to 2007, the annual average runoff of the two hydrologic stations, namely Yongjinghong and Kratie, was 388 mm and 649 mm, respectively. The annual average baseflow of the two hydrologic stations was 199 mm and 359 mm, respectively. The annual average BaseFlow Index (BFI), namely the

Table 3.7 The evaluation result of the 9 baseflow separation methods

Methods	Yongjinghong		Kratie	
	KGE	*BIAS* (%)	*KGE*	*BIAS* (%)
UKIH	0.82	7.9	0.80	17.1
Local	0.86	7.1	0.74	20.1
Fixed	0.83	10.1	0.72	22.5
Slide	0.80	11.1	0.73	21.0
LH	0.70	16.8	0.62	28.6
Chapman	0.67	19.2	0.72	20.5
CM	0.43	23.2	0.67	25.3
EWMA	0.85	6.7	0.84	14.0
Eckhardt	0.86	6.0	0.93	5.8

Table 3.8 Annual average runoff, baseflow and BFI for the two hydrological stations from 1980 to 2007

Stations	Runoff (mm)	Baseflow (mm)	*BFI*
Yongjinghong	388	199	0.51
Kratie	649	359	0.55

ratio of baseflow to streamflow, of the two hydrologic stations was 0.51 and 0.55, respectively (Table 3.8). The annual BFI of the Yongjinghong Station from 1980 to 2007 showed a significant ($p < 0.05$) downward trend, with a value of -0.001 yr^{-1}, while the annual BFI of the Kratie Station showed a significant ($p < 0.05$) upward trend, with a value of 0.09 yr^{-1} (Fig. 3.22). The annual baseflow of the Yongjinghong Station from 1980 to 2007 showed a nonsignificant ($p = 0.22$) downward trend, with a value of -0.77 mm/yr, while the annual baseflow of the Kratie Station showed a significant ($p < 0.05$) upward trend, with a value of 7.22 mm/yr.

From 1980 to 2007, the maximum and minimum average monthly BFI of Yunjinghong Station were in December (0.75) and June (0.34), respectively (Fig. 3.22). The maximum and minimum average monthly baseflow of Yunjinghong Station were in September (34 mm) and April (6 mm), respectively. The maximum and minimum average monthly BFI of Kratie Station were in December (0.62) and June (0.46), respectively. The maximum and minimum average monthly baseflow of Kratie Station was in September (80 mm) and February (7 mm), respectively.

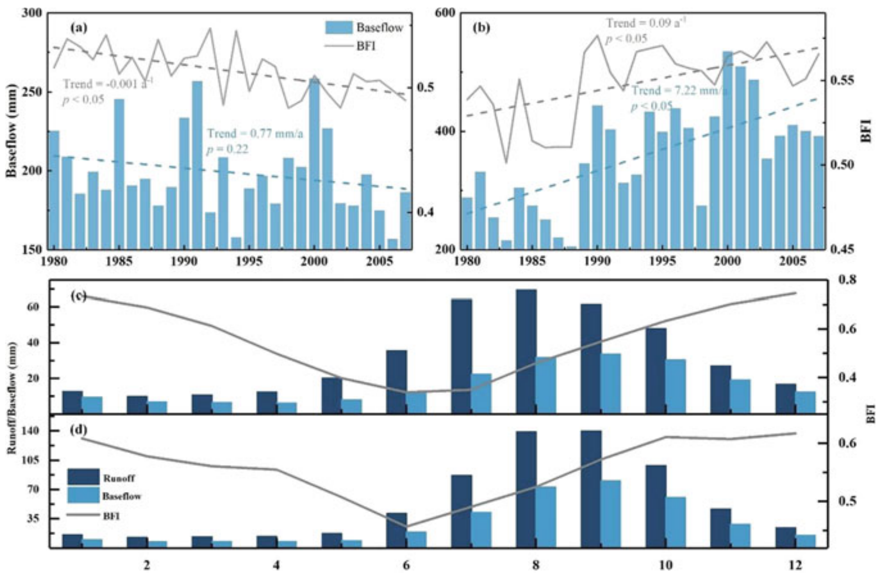

Fig. 3.22 The annual baseflow and BFI (**a**, **b**), and average monthly runoff, baseflow and BFI (**c**, **d**) from 1980 to 2007 for the two hydrological stations Yongjinghong (**a**, **c**) and Kratie (**b**, **d**)

3.3.3 Influencing Factors of Baseflow [Xiaomang Liu]

For a basin, climatic factors have the most direct impact on the baseflow (Brutsaert, 2005). Climatic factors influence baseflow by altering rates of evapotranspiration, infiltration and recharge, and timing of snowmelt runoff (Tague & Grant, 2009; Winograd et al., 1998). Additionally, baseflow is also influenced by different basin characteristics, including climate conditions, soils, topography, and land cover.

Figure 3.23 shows scatterplots of monthly baseflow versus four climatic factors, namely precipitation (Pr), surface shortwave radiation (SSR), wind speed (u), and air temperature (Ta), for the two hydrologic stations, namely Yongjinghong and Kratie. For Yongjinghong Station, significant ($p < 0.05$) positive correlations were found between baseflow and the two climate factors, namely Pr and Ta, and the values of Pearson's correlation (r) were 0.56 and 0.50, respectively. Significant ($p < 0.05$) negative correlations were found between baseflow and the other two factors, namely SSR and u, and the values of r were −0.24 and −0.60, respectively. For Kratie Station, both Pr and Ta were significantly ($p < 0.05$) positively correlated with baseflow, and the values of r were 0.67 and 0.39, respectively. Both SSR and u were significantly ($p < 0.05$) negatively correlated with baseflow, and the values of r were −0.47 and −0.46, respectively. Thus, baseflow is significantly affected by the four climatic factors in the Lancang-Mekong River Basin.

3.3.4 Projected Change in Baseflow

Although the Eckhardt method can accurately estimate baseflow, the method needs daily streamflow as input, while accurate daily streamflow estimates are not available for the future. Therefore, models are needed to simulate the future baseflow. Past studies have shown that mechanism models, such as hydrological models and land surface models, have low accuracy in simulating baseflow (Bai et al., 2016). This is due to the groundwater simulation of the hydrologic model and the land surface model being relatively simple (Lo & Famiglietti, 2010). In this study, a machine learning approach, namely the Long Short-Term Memory network, was used to estimate the future baseflow based on data from the Coupled Model Intercomparison Project phases 6 (CMIP6).

3.3.4.1 The Long Short-Term Memory (LSTM) Network

The LSTM network is a state-of-art machine learning approach for time series forecasting (Hochreiter & Schmidhuber, 1997). It has the advantage of remembering information for a long period, namely long-time memory (Kratzert et al., 2018; Shen, 2018; Zhang et al., 2018). This advantage benefits monthly baseflow estimation and

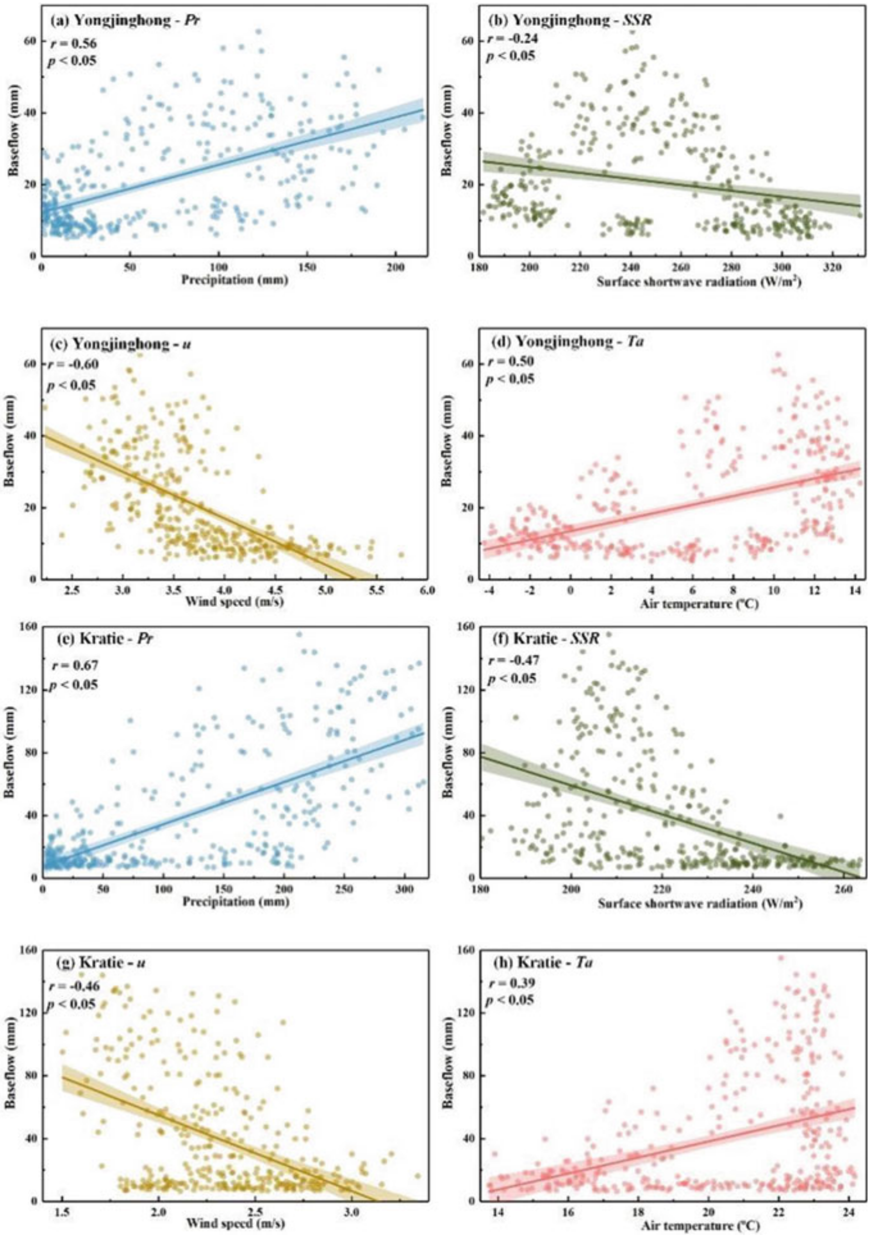

Fig. 3.23 The relationships between the monthly baseflow and the four climatic factors for Yongjinghong Station (**a**–**d**) and Kratie (**e**–**h**). r value is the Pearson correlation coefficient. The shaded bands represent 95% confidence intervals for the regressions

prediction by learning long-term dependencies between baseflow and previous basin conditions.

The Long Short-Term Memory (LSTM) network is structured as a collection of interconnected memory blocks, with each block consisting of several key components: a cell state, input gate, output gate, and forget gate, along with the hidden state. The cell state functions as the system's memory, retaining crucial information. The three gates, namely the input gate, output gate, and forget gate, enable the network to selectively store and retrieve important information from past time steps while discarding irrelevant data (Kratzert et al., 2018). The details of the LSTM network can refer to Hochreiter and Schmidhuber (1997) and Kratzert et al. (2019). In this study, the LSTM network was constructed using the deep learning toolbox available in MATLAB. Four related climatic factors, namely monthly precipitation (Pr), air temperature (Ta), surface shortwave radiation (SSR), and wind speed (u), were used to estimate and predict monthly baseflow based on Sect. 3.3.3.

3.3.4.2 Data and Method

Historical data of the four variables from 1980 to 2014 were obtained from Princeton Global Meteorological Forcing Dataset (Sheffield et al., 2006; Zhang et al., 2018), with a spatial resolution of 0.5°. Future data on these variables from 2015 to 2100 were obtained from 26 general circulation models (GCMs) in the CMIP6 (Table 3.9). Simulations from four shared socioeconomic pathways (SSPs), drawn from Tier 1 of ScenarioMIP: SSP1-2.6 (+2.6 W/m^2 imbalance; low forcing sustainability pathway), SSP2-4.5 (+4.5 W/m^2; medium forcing middle-of-the-road pathway), SSP3-7.0 (+7.0 W/m^2; medium- to high-end forcing pathway), and SSP5-8.5 (+8.5 W/m^2; high-end forcing pathway), were used (O'Neill et al., 2016). The bilinear interpolation method was used to downscale all the variables to a common horizontal grid at $0.5° \times 0.5°$ resolution. To proceed with further analysis with reduced biases, the perturbation method was used to perform bias correction against observed data.

The classic split sample test scheme (KlemeŠ, 1986) was used for calibration and validation of the LSTM. The available data in the basin was split into two sub-periods, namely sub-period I and sub-period II, which were used to calibrate and validate the LSTM, respectively. The LSTM was calibrated in sub-period I (1980–1999) and validated in sub-period II (2000–2007). The Nash–Sutcliffe efficiency (NSE) between simulated and observed baseflow was taken as the objective function to train the LSTM. The KGE and BIAS were used to evaluate the accuracy of model estimation.

3.3.4.3 Estimating and Predicting Baseflow with the LSTM Model

Generally, the LSTM model performed well in the calibration and validation periods for the two hydrologic stations, namely Yongjinghong and Kratie (Table 3.10). In the calibration period, the KGE values between the observed and simulated baseflow

Table 3.9 The information of the 26 GCMs in the CMIP6

No.	ESM	Center	Realisations	Resolution (km)
1	ACCESS-CM2	CSIRO-ARCCSS, Australia	r1i1p1f1	144 × 192
2	ACCESS-ESM1-5	CSIRO, Australia	r1i1p1f1	145 × 192
3	BCC-CSM2-MR	BCC, China	r1i1p1f1	160 × 320
4	CanESM5	CCCma, Canada	r1i1p1f1	64 × 128
5	CanESM5-CanOE	CCCma, Canada	r1i1p2f1	64 × 128
6	CESM2	NCAR, USA	r1i1p1f1	192 × 288
7	CESM2-WACCM	NCAR, USA	r1i1p1f1	192 × 288
8	CNRM-CM6-1	CNRM-CERFACS, France	r1i1p1f2	128 × 256
9	CNRM-ESM2-1	CNRM-CERFACS, France	r1i1p1f2	128 × 256
10	EC-Earth3	EC-Earth-Consortium	r1i1p1f1	256 × 512
11	EC-Earth3-Veg	EC-Earth-Consortium	r1i1p1f1	256 × 512
12	FGOALS-f3-L	CAS, China	r1i1p1f1	180 × 288
13	FGOALS-g3	CAS, China	r1i1p1f1	80 × 180
14	GFDL-ESM4	NOAA-GFDL, USA	r1i1p1f1	180 × 288
15	GISS-E2-1-G	NASA-GISS, USA	r1i1p1f2	90 × 144
16	HadGEM3-GC31-LL	MOHC, UK	r1i1p1f3	144 × 192
17	INM-CM4-8	INM, Russia	r1i1p1f1	120 × 180
18	INM-CM5-0	INM, Russia	r1i1p1f1	120 × 180
19	IPSL-CM6A-LR	IPSL, France	r1i1p1f1	143 × 144
20	MIROC6	JAMSTEC/AORI/NIES/R-CCS, Japan	r1i1p1f1	128 × 256
21	MIROC-ES2L	JAMSTEC/AORI/NIES/R-CCS, Japan	r1i1p1f2	64 × 128
22	MPI-ESM1-2-h	MPI-M, Germany	r1i1p1f1	192 × 384
23	MPI-ESM1-2-LR	MPI-M, Germany	r1i1p1f1	96 × 192
24	MRI-ESM2-0	MRI, Japan	r1i1p1f1	160 × 320
25	NorESM2-MM	NCC, Norway	r1i1p1f1	192 × 288
26	UKESM1-0-LL	MOHC, UK	r1i1p1f2	144 × 192

for the two hydrologic stations are 0.90 and 0.92, respectively. The BIAS values between observed and simulated baseflow for the two hydrologic stations are 1.3% and 1.6%, respectively. In the validation period, the median KGE values for the two stations are 0.87 and 0.75 respectively, and the BIAS values are 11.0% and 16.8% respectively. Thus, the trained LSTM model was used to estimate the future monthly baseflow.

Table 3.10 Performance of the LSTM model for the two hydrological stations

Stations	Calibration period		Validation period	
	KGE	*BIAS (%)*	*KGE*	*BIAS (%)*
Yongjinghong	0.90	1.3	0.87	11.0
Kratie	0.92	1.6	0.75	16.8

The trained LSTM model was used to estimate and predict the monthly baseflow from 1980 to 2100 for the two hydrologic stations. Figure 3.24 shows the time series of annual baseflow and BFI for the two hydrological stations from 1980 to 2100. Annual baseflows for the two hydrological stations in the four scenarios, namely SSP1-26, SSP2-45, SSP3-70, and SSP5-85, all have increasing trends, and the BFI in the four scenarios all have a slightly increasing trend. Table 3.11 shows the average annual baseflow and BFI for the two hydrological stations from 2015 to 2100. It could be found from Table 3.11 that the volume of baseflow from the Yongjinghong station upstream is much lower than that of Kratie station downstream, while the BFI is just slightly lower. And with the intensification of climate change and human activities, the baseflow at both the upstream and downstream increases and that at the upstream increases faster than that of the downstream, but the BFIs keep consistent, implying that the total streamflow doesnot have a similar increasing trend.

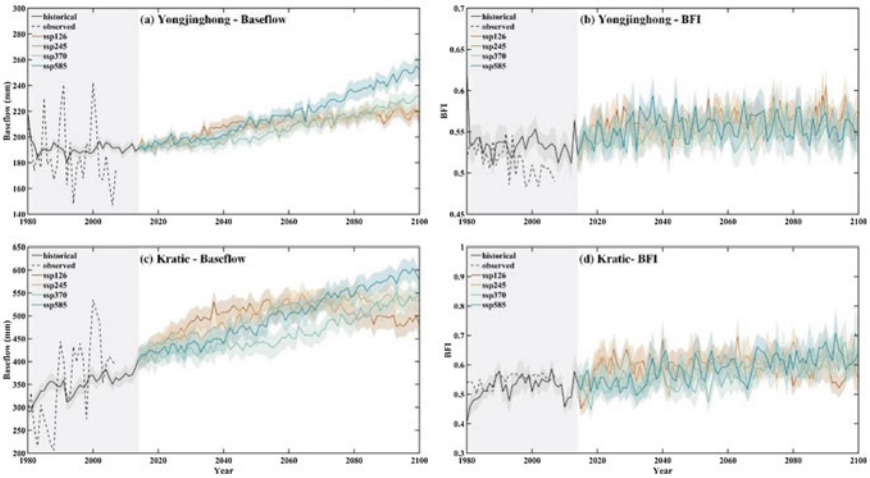

Fig. 3.24 Annual baseflow and BFI from 1980 to 2100 for the Yongjinghong station (**a**, **b**) and Kratie station (**c**, **d**) for the four scenarios. The shading denotes the 95% confidence intervals of the 26 models

Table 3.11 Annual average baseflow and BFI for the two hydrological stations from 2015 to 2100 in the four scenarios

Scenarios	Yongjinghong		Kratie	
	Baseflow (mm)	*BFI*	Baseflow (mm)	*BFI*
SSP1-26	210 ± 13	0.56 ± 0.02	498 ± 86	0.59 ± 0.07
SSP2-45	208 ± 13	0.56 ± 0.02	501 ± 85	0.60 ± 0.07
SSP3-70	207 ± 16	0.55 ± 0.03	462 ± 82	0.56 ± 0.09
SSP5-85	218 ± 16	0.56 ± 0.03	501 ± 83	0.57 ± 0.09

3.4 Dynamics of Inundation Area and Water Turbidity in Tonle Sap Lake

3.4.1 Inundation Area Detection

Tonle Sap Lake (TSL) in Cambodia stands as the largest lake in Southeast Asia, playing a pivotal role as one of the world's most productive lake-wetland systems. This remarkable ecosystem supports approximately 1.7 million people who depend on it for their livelihoods. What sets TSL apart is its distinctive "flood pulse" phenomenon, marked by seasonal water level fluctuations between the wet and dry seasons, creating a periodically inundated floodplain. This dynamic floodplain offers unique habitats for seasonally migratory fish species and receives a vital influx of nutrients from the Mekong River. It serves as a critical source of freshwater resources and preserves essential habitats for numerous endangered species. Furthermore, the flood regime of TSL exerts a significant influence on land cover changes, such as delineating the extent of cropland in the floodplain and impacting alterations in forest cover. Consequently, Tonle Sap Lake holds the status of being the "heart of the lower Mekong" as regional socio-economic development and the sustainability of the ecosystem profoundly rely on the intricate dynamics of this "flood pulse."

The boundary of Tonle Sap Lake was firstly defined before the inundation area extraction, which is the buffered extent that was larger than the maximum possible inundation area of the open water body of the lake (Lin & Qi, 2017). This definition is different from previous studies that also considered the entire floodplain as Tonle Sap Lake (Arias et al., 2012; Frappart et al., 2018; Sakamoto et al., 2007), and the currently used boundary excluded most of the area in the floodplain of Tonle Sap Lake. Such exclusion is because of the difficulty in estimating the surface area of the entire floodplain when using optical remote sensing data, where the water is hidden beneath the flooded forest. The inundation areas were extracted based on a normalised difference vegetation index (NDVI) (Mcfeeters, 1996; Verhoef, 1996). Note that the NDVI thresholds to separate water and land may differ among images. To overcome this challenge, a self-developed interactive graphical user interface (GUI) by Hou et al. (2018) was used to determine the optimal image-specific threshold. We further visualised the resulting land/water boundaries to assure the best consistency with the largest contrasts over NDVI images.

3.4.2 Modelling Inundation Areas and Their Change

Inundation in the Tonle Sap Lake region is governed by the (1) reversed flow in the Tonle Sap river, (2) inflow from the lake tributaries, and (3) direct rainfall on the lake system. The lake's floodplains extend into 12,000–15,000 km^2 area during the wet season, storing 50–80 km^3 of water, which shrinks to ~2,400 km^2 during the dry season with a water storage of 1.5–3.0 km^3. The lake water levels during these wet-dry transitions vary between ~1.4 to ~9.0 m (Arias et al., 2012; Chen et al., 2021a, 2021b; Frappart et al., 2018; Kummu & Sarkkula, 2008; Kummu et al., 2014; Pokhrel et al., 2018a). Besides the permanently flooded lake portion, substantial areas in its periphery are flooded seasonally with varied flood occurrence during average, wet, and dry years (Fig. 25X; Dang et al., 2022). The dry–wet variation in flooded areas within a year serves as an important detention reservoir to provide increased dry season flow in the Mekong Delta region. The flooded areas vary vastly not only seasonally but also from year to year depending on regional climate variability and the water levels in the mainstream Mekong River that drive the flow reversal in the Tonle Sap River. On an average basis over long terms, ~54% of the inflow to the Tonle Sap Lake comes from the Mekong River either through flow reversal in the Tonle Sap River or by overland flooding, and the rest is contributed by inflow from the tributaries (~34%) and precipitation over the lake (~12%) (Kummu et al., 2014) (Fig. 3.25).

Numerous studies have examined how the inundated areas in the Tonle Sap Lake floodplain have been changing in the past few decades by using hydrological-hydrodynamic modelling and remote sensing data. For example, Lin and Qi (2017) mapped the open water areas in the Tonle Sap Lake from 2001 to 2015 using remote sensing products and showed large inter-annual variability, also noting a consistent decline in open water areas during that period. They attributed such shrinking

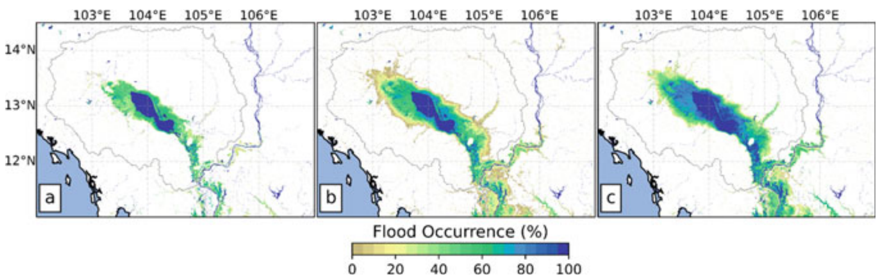

Fig. 3.25 Average flood occurrence (% time during a year) of the Tonle Sap Lake area in a dry year (**a**, 2015), long-term average (**b**, between 1979 and 2016) and a wet year (**c**, 2000)

of the lake to the rapid increase in dam construction in the Mekong River Basin during the same period, but their study did not explicitly isolate the effects of dams versus climate change and variability. Another recent study (Frappart et al., 2018) used remotely sensed data to map inundation extents during the 1993–2017 period, finding that interannual anomalies of the lake surface water storage variations are more related to precipitation fluctuation outside of the Tonle Sap watershed with discharge from the Mekong River being the major influence. The study by Ji et al. (2018) used the Modified Normalised Difference Water Index (MNDWI) based on MODIS satellite data for 2000–2014 period. They suggested a decline in water surface area, especially after 2008, by 8.3% and 1.5% during the flood and dry seasons, respectively. This study also indicated a more dominant role of rainfall in the Mekong River Basin than that of the rainfall in the lake watershed on the variation of water areas in the lake, but also noted that the construction and operation of new dams in the Lancang river could not be directly linked to the decline in the lake area. Instead, they indicated that the increased runoff due to dam release during the dry season could have mitigated the decline in surface area during the dry season. These findings are in line with a potential increase in dry-season flow and water levels when the mainstream Mekong flow is regulated by upstream dams (Pokhrel et al., 2018b).

Chen et al. (2021a, 2021b) conducted a study revealing notable declines in water levels and inundation areas during the dry season and throughout the entire year since the late 1990s. These declines occurred alongside increased sub-decadal variability in the region. The study also identified decreasing probabilities of encountering high inundation areas and increasing probabilities of encountering low inundation areas for the period from 2000 to 2019 when compared to the return period of inundation areas for the years 1986 to 2000 and 1960 to 1986. Furthermore, the research unveiled a shift in the mean seasonal cycle of daily water levels, with a 10-day shift in the dry season and a 5-day shift in the wet season between the periods 2000–2019 and 1986–2000. The study also established significant correlations and changes in coherence between water levels and large-scale atmospheric circulations, including El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Indian Ocean Dipole (IOD). These findings suggest that atmospheric circulations exerted influences on the flood pulse at various time scales. Additionally, changes in discharge at the Mekong mainstream were observed, indicating that anthropogenic factors may have played a role in impacting the high water levels in the lake. In summary, the study points to a diminishing flood pulse in the Tonle Sap Lake region since the late 1990s. These previous studies assume that water infrastructure development and climate change are the main factors affecting the inundation extent and duration in the Tonle Sap Lake region. However, a recent study by Ng and Park (2021) that used remote sensing products for 1980–2018 period highlighted the role of intensified local sand mining at Phnom Penh and Prek Kdam, which could have lowered the riverbed at the entrance from the Mekong mainstream to the lake and significantly impacted lake inundation dynamic. While these studies have provided crucial information on the changing inundation dynamics of the Tonle Sap Lake, the results suffer from uncertainties arising from missing data, cloud contamination, effect of vegetation, and inherent uncertainties in satellite products.

Hydrological modelling can fill the data gaps by providing spatially complete and temporally continuous simulations; however, realistic simulations require accurate input data and model parameters, which are not abundantly available for the Tonle Sap Lake region. Numerous modelling studies have been conducted for the Tonle Sap Lake. Kummu et al. (2014) presented a detailed modelling and water balance analysis of the Tonle Sap Lake system using an integrated framework that employed a digital bathymetry model, water level-area-volume relationship and the EIA 3D hydrodynamic model (Kummu et al., 2006). They provided a detailed water balance of the lake, including inundated areas, timing of flow reversal in the Tonle Sap River, and various other related hydrodynamic attributes of the lake. They also suggested that the lake water level is primarily governed by water levels in the Mekong River, and noted that a relatively small change in water level would inundate large areas of the floodplain.

3.4.3 Water Turbidity Estimation

To investigate the potential impacts of lake inundation changes on water turbidity, the concentrations of total suspended sediments (TSS) were quantitatively retrieved using remote sensing images. Various methods have been developed previously to estimate the TSS concentrations of inland and coastal waters using satellite observations, with the algorithms ranging from empirical (Doxaran et al., 2002; Feng et al., 2012; Hou et al., 2018; Nechad et al., 2010) to semianalytical approaches (Dekker et al., 2001). The underlined theory of these algorithms is the sensitivity of the TSS concentration to red and NIR reflectance (Feng et al., 2012; Tassan, 1994), where the signals increase with TSS increases, owing to the enhanced backscattering of suspended particles (Babin et al., 2003). In this study, a red band-based algorithm, previously used in both Tonle Sap Lake (Hoshikawa et al., 2019) and various other global waters (Miller and McKee 2004), was established in this work by using concurrent MODIS reflectance and in situ TSS concentrations, expressed as follows:

$$\text{TSS}\left(\text{mg L}^{-1}\right) = 10.32\,\text{e}^{21.72\times\Omega}(\Omega = R_{645}) \tag{3.3}$$

where R_{645} is the MODIS surface reflectance product in the 645 nm band, which has been proven to be effective in TSS estimation in lacustrine waters (Feng et al., 2018). Indeed, the feasibility of this algorithm can be indicated by the high correlation (R^2 = 0.84), small root mean square error (34.2%) and large TSS range (8.6–398.0 mg L^{-1}) (see Fig. 3.26).

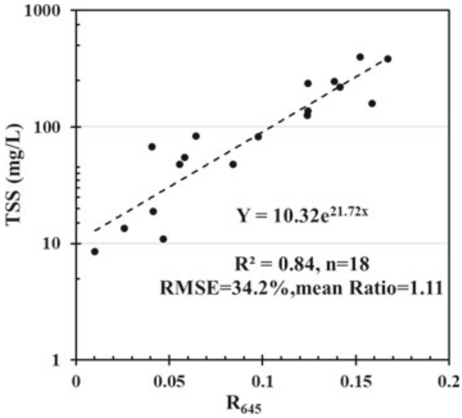

Fig. 3.26 Calibration of a remote sensing model to retrieve TSS concentrations in Tonle Sap Lake using MODIS red band (Wang et al., 2020)

3.4.4 *Long-Term Evolution of Inundation Area and Water Turbidity*

Figure 3.27a displays the monthly mean inundation areas of Tonle Sap Lake for the period between 1988 and 2018, determined from both Landsat (red) and MODIS (black) data. Additionally, the monthly mean climatological inundation areas, which represent multiyear monthly means estimated using MODIS data, are plotted as green dashed lines. Points falling above the green line indicate that the current month's inundation value exceeded the monthly climatology, and vice versa. To analyze inundation trends over the past three decades, monthly anomalies were calculated as deviations from the monthly climatologies (in percent), as shown in Fig. 3.27b. Throughout the observed period, the inundation area of Tonle Sap Lake exhibited considerable variability, ranging from 3599.8 km^2 in October 2001 to 2304 km^2 in March 2013. These values experienced rapid fluctuations due to pronounced seasonal changes influenced primarily by shifts in regional precipitation and interactions between the river and the lake (Frappart et al., 2018).

However, superimposed on these substantial seasonal cycles is a noticeable trend of lake shrinkage in recent years. There is clear evidence of decreased inundation in most years over the past two decades (see Fig. 3.27a, b). Specifically, the decreasing patterns from 2000 to 2018 were consistent between MODIS and Landsat observations, despite differences in their data availabilities. This shrinking trend is further underscored by the consistent declines in the annual mean (8.22 km^2 per year, significant at $P < 0.05$), annual minimum (5.93 km^2 per year, significant at $P < 0.05$), and annual maximum (17.82 km^2 per year, significant at $P < 0.05$) inundation areas, as derived from MODIS-extracted data for the period between 2000 and 2018 (see Fig. 3.28). Furthermore, although statistically insignificant, a decreasing trend was also observed in the annual maximum and minimum ratio ($P > 0.05$), indicating a reduced strength of the flood pulse between the dry and wet seasons during the MODIS observational period (see Fig. 3.28d).

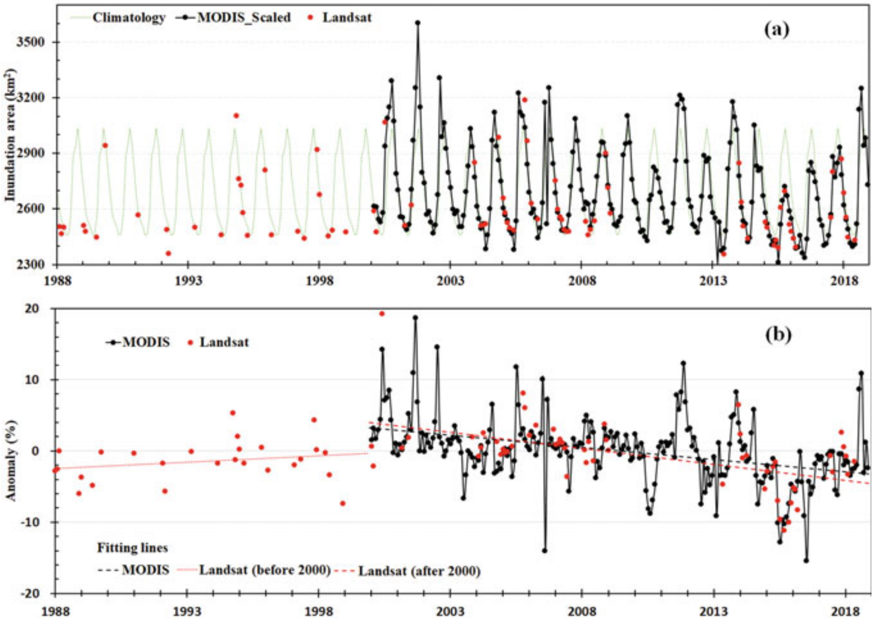

Fig. 3.27 Monthly mean inundation area of Tonle Sap Lake between 1988 and 2018 obtained using the MODIS and Landsat observations (Wang et al., 2020)

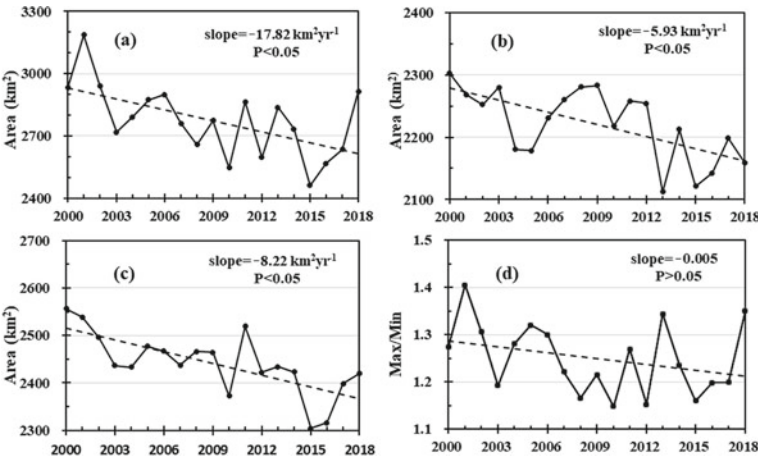

Fig. 3.28 MODIS observed annual **a** maximum, **b** minimum, **c** mean and **d** maximum/minimum inundation areas of Tonle Sap Lake (Wang et al., 2020)

Figures 3.29 and 3.30 show the annual mean TSS maps and zonal mean values of Tonle Sap Lake from 2000 to 2018. The annual mean TSS concentration of the entire lake showed a statistically significant increasing trend between 2000 and 2018 (see Fig. 3.30a, 7.92 mg L^{-1} yr^{-1}, $P < 0.05$). In terms of seasonal patterns, significant TSS increasing trends were detected in quarters 1 and 4, whereas nonsignificant trends were identified in quarters 2 and 3 (Fig. 3.30b–e). Moreover, remarkable spatial heterogeneity was revealed in the TSS concentration maps. In particular, in most of the years, riverine estuaries in the southeastern, northwestern, and northern parts of the lake showed consistently higher values (sediment plume). The significant seasonal TSS dynamics can partially explain the spatial heterogeneities of the annual TSS maps. The zonal mean TSS concentration of the entire lake was generally <100 mg L^{-1} (bluish to greenish) before 2004, and such values reached above 100 mg L^{-1} in most of the later years. Spatially, TSS increase could be found in almost every location of the lake (see the last panel of Fig. 3.29).

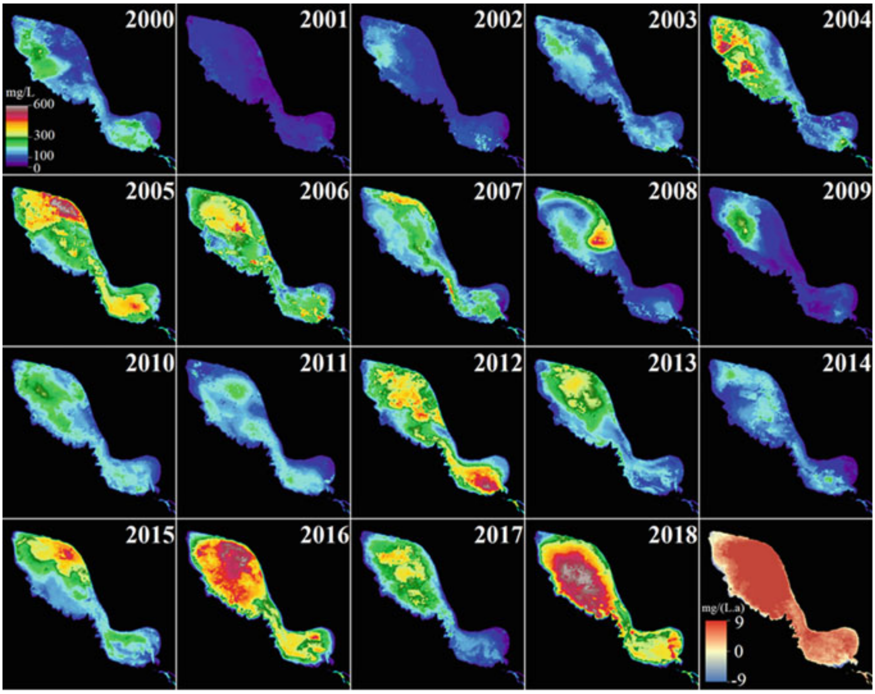

Fig. 3.29 Annual mean TSS concentration maps of Tonle Sap Lake from 2000 to 2018. The last panel shows the change rate for the annual mean TSS concentration at each location in Tonle Sap Lake between 2000 and 2018 (Wang et al., 2020)

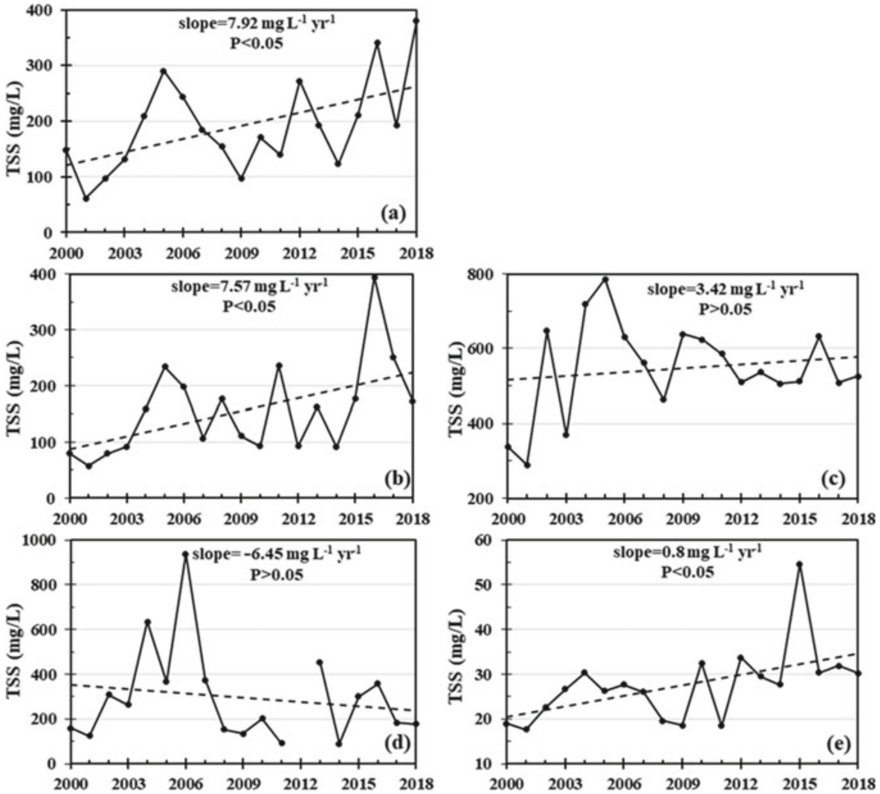

Fig. 3.30 Long-term mean values of TSS concentration in the Tonle Sap Lake. **a** annual mean, **b**–**e** quarterly mean from quarter 1–4 (Wang et al., 2020)

3.4.5 Drivers of Change in Inundation Area and Water Turbidity

Figure 3.31a reveals the identification of a high correlation zone (HCZ) marked with black dots, situated in the northern region of the Tonle Sap Lake drainage basin, depicted by yellowish to reddish coloring, encompassing more than 50% of the entire Mekong River Basin. Analyzing the change rate in annual mean precipitation between 2000 and 2016 (as shown in Fig. 3.31b), it becomes evident that approximately one-third of locations within the HCZ exhibit a statistically significant decreasing trend in precipitation. In contrast, most regions outside the HCZ display insignificant correlations. Notably, the year-to-year fluctuations in mean precipitation within the HCZ closely mirror those observed in the inundation area of Tonle Sap Lake, with a robust correlation (R2 = 0.67, significant at $P < 0.05$) (Fig. 3.31d). Similarly, a strong correlation exists between the annual mean runoff at Kratie station and the precipitation within the HCZ (R2 = 0.68, significant at $P < 0.05$) (Fig. 3.31e). Consequently,

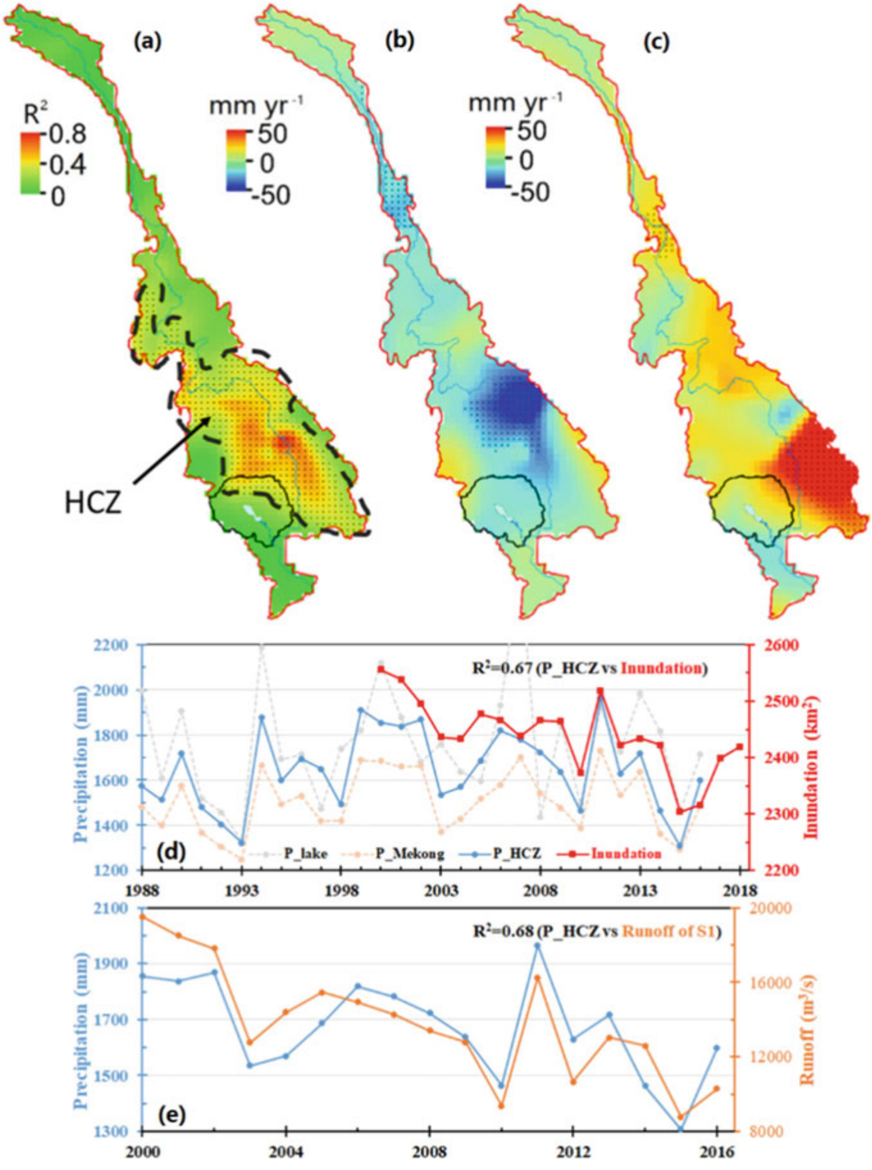

Fig. 3.31 Correlations (R2) between the annual mean precipitation at each location in the Mekong River Basin and the annual mean inundation area of Tonle Sap Lake between 2000 and 2016. **b** Annual mean precipitation change rate from 2000 to 2016 for each location in the Mekong River Basin; **c** same as **b** but with a period from 1988 to 2000. The black dots in (**a**–**c**) represent pixels with statistically significant ($P < 0.05$) precipitation trends. **d** Long-term annual mean precipitation throughout Tonle Sap Lake (P_lake), the Mekong River Basin (P_Mekong), and the HCZ (P_HCZ). **e** Long-term patterns and correlations between annual mean precipitation of the HCZ (P_HCZ) and runoff discharge of the Mekong River at Kratie (Wang et al., 2020)

it can be deduced that the recent reduction in Tonle Sap Lake's inundation area is intimately linked with the decline in runoff in the Mekong River and the decrease in precipitation within the HCZ.

The HCZ is situated in the lower basin of the Mekong River, predominantly outside the drainage basin of Tonle Sap Lake. Recent reductions in precipitation within the Mekong River Basin have previously been linked to El Niño/La Niña events, as well as the Indian and Western North Pacific Monsoons (Frappart et al., 2018). Previous research has suggested that the decreased runoff from the Mekong River was primarily a consequence of climate change rather than human interventions, such as upstream dam construction in China. In contrast, there were no significant trends in precipitation for most of the Mekong River Basin between 1988 and 2000 (Fig. 3.31c), which could potentially explain the stabilized inundation observed during this period (see Fig. 3.25). To assess the relative impacts of three potential factors on the interannual inundation changes of Tonle Sap Lake, a multiple general linear model was employed (Tao et al., 2015). These factors included the precipitation of the HCZ, the number of dams, and the evapotranspiration (ET) of the lake's drainage basin. The analysis revealed that the relative contributions were 76.1% for HCZ precipitation, 6.9% for the number of dams, and 2.0% for ET, respectively. These findings underscore the predominant role of HCZ precipitation changes in driving the interannual dynamics of the lake's inundation.

The water turbidity of the Tonle Sap Lake is likely to be controlled by two factors: (1) Sediment resuspension, which can be attributed to external forces such as wind activity within the lake, sediment discharge within the lake basin, as well as internal forces related to hydrodynamics (Hoshikawa et al., 2019); and (2) exchanges of sediments between the Tonle Sap Lake and the Mekong River. Satellite observations showed a pronounced increase in water turbidity, which was likely due to the lake shrinkage induced hydrodynamic changes. For example, higher chances of sediment resuspension from the bottom can be expected when water depth decreases, even if other external factors are stable. Indeed, it was further confirmed that the validity of this hypothesis by the statistically significant correlations between the annual TSS concentration and inundation area (R2 = 0.41 for quarter 1 and R2 = 0.49 for quarter 4, both with $P < 0.05$, see Fig. 3.32a, d). Such correlations agreed well with the results of a former study (Hoshikawa et al., 2019), where statistically significant relationships were detected between water depth and TSS in dry seasons. Therefore, the inundation shrinkage (i.e., water depth decline) has caused an increase in sediment resuspension through either wind or gravity flow and therefore lead to the recent increase in water turbidity in Tonle Sap Lake (Siev et al., 2018). In contrast, the TSS trend and TSS- inundation correlations in quarters 2 and 3 were insignificant, which were associated with the reversed flow of the Mekong River to Tonle Sap Lake that was intervented by human activities during these periods (Fig. 3.32b, c). Numerically, sediment flux from the Tonle Sap River to the lake varies between 5.1 and 6.4 Mt year^{-1}, whereas the magnitude of reversal sediment discharge from the lake to the river was about three times smaller (Kummu & Sarkkula, 2008; Sok et al., 2021). As such, the lake turbidity could be substantially modulated by the sediment-rich flows from the Mekong River, which smears the inundation shrinkage-induced impacts in

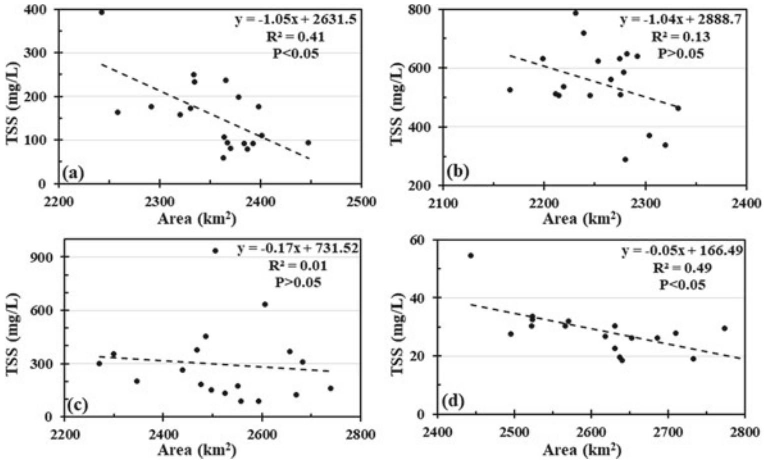

Fig. 3.32 Relationships between the seasonal mean TSS and inundation areas of Tonle Sap Lake. **a**–**d** Quarters 1–4 (Wang et al., 2020)

wet seasons. Nevertheless, physical modelling and additional in situ hydrological measurements are required to determine the underlined mechanisms and to quantify the exact contributions of various drivers on the inundation and water turbidity.

3.4.6 Projected Change in Inundation Area

Numerous studies have used hydrological models to simulate and quantify the future changes in the Tonle Sap Lake's inundation dynamics under various scenarios representing both climate variability and water infrastructure development plans. For example, Västilä et al. (2010) used multiple models including GCM, VIC, EIA to examine the effects of changes in sea level and Mekong mainstream discharge under climate change on the Lower Mekong flood pulse during 2010–2049 period. They found that water levels in the Lower Mekong, including the Tonle Sap Lake, would increase in the future, leading to higher annual flooded areas. In particular, annual maximum water depth and flooded areas increased during average and dry years and decreased during wet years. The study also reported that flood duration will be likely to increase slightly with greater flooding starting earlier and lasting longer with flood peaks arriving earlier in average hydrological years. Arias et al. (2012) evaluated the impact of water infrastructure development and climate change by using the MRC Decision Support Framework for multiple scenarios of progressive stages in comparison to simulations by Västilä et al. (2010). They reported that while hydropower development could reduce flood extent by up to 1,200 km^2, climate change is expected to increase flood extent by up to 1,000 km^2. They also noted that during average years in the future, water levels in the lake during October–November may increase due to climate change but reduce due to dam construction. The largest changes may occur during dry years, and the areas most impacted would be those at the fringe of the open water with flood duration of 9–10 months, and halfway between open water and the edge of the floodplain, flooded for ~4 months. A recent study also showed similar results based on hypothetical dam simulations, indicating that regulation of mainstream Mekong flow by dams may increase areas flooded for over 7 months and reduce those flooded for less than 5 months (Pokhrel et al., 2018b). Similar findings have been reported by Yu et al. (2019) using CAESAR-LISFLOOD system and by Try et al. (2020) using RRI model. Further, Arias et al. (2014) identified that areas that currently have long periods or are permanently inundated throughout the year are likely to expand while seasonally inundated areas will be decreased. They also found that the hydrological alteration of the hydropower system in the 3S basin could have similar effects as the Lancang dam cascade and the cumulative effect of development in both areas will cause significant disruption to the inundation pattern of the lake.

3.5 Past and Future Changes in Climate and Water Resources in the LMRB

3.5.1 Climate of the Lancang-Mekong River Basin

3.5.1.1 Past and Future Warming Trends

In the past decade, there have been notable and confidently increasing trends in the annual mean temperature across the LMRB (Fan et al., 2015). These warming trends in both the Lancang River Basin and Mekong River Basin have surpassed the global average temperature rise, which was reported as 0.17 °C per decade since 1981 by Hartfield et al. (2018).

Between the early 1980s and 2010, there were no statistically significant changes in annual maximum and minimum temperatures observed over the Lancang River Basin (Fan et al., 2015). However, it's noteworthy that both annual maximum and minimum temperatures exhibited the same warming trend direction as the mean annual temperature in the Mekong River Basin during the same period (Lutz et al., 2014). Among the seasons, the highest rate of warming trends was observed during winter (December–February) across both the Lancang River Basin (Fan et al., 2015) and the Mekong River Basin (Lutz et al., 2014) from 1981 to 2010. It's worth mentioning that the Lancang River Basin had already been experiencing warmer winters prior to 1981, particularly during the period from the 1960s to the early 2000s (You et al., 2010).

Projections for the twenty-first century indicate statistically significant warming trends in mean annual temperature over the Lancang-Mekong River Basin (Kingston et al., 2011; Lacombe et al., 2012). These trends are expected to be more pronounced in the northern and southern parts of the basin (Lauri et al., 2012). However, it's important to note that the extent of temperature change varies depending on the climate scenario used in the models. Over the Mekong River Basin, a warming trend of 0.01–0.03 °C per decade is projected (Zhou et al., 2013), while the Lancang River Basin is expected to experience slightly more evident and consistent warming (Kingston et al., 2011). Projections suggest that by 2050, the daily maximum temperature over the Mekong River Basin is likely to increase, with estimates ranging from 1.6 °C in the northern and southwestern regions to 4.1 °C in the southeastern areas, where the historical climate has been cooler than in the central part of the basin (Zhou et al., 2013). Consequently, an increase in the frequency of annual hot days (daily maximum temperature >33 °C) is anticipated, particularly in the southern part of the Mekong River Basin (Västilä et al., 2010). Regarding seasonal temperature changes, projections indicate a fairly homogeneous increase in temperatures across the Mekong River Basin, with a warmer climate expected during wet seasons (1.7–5.3 °C) compared to dry seasons (1.5–3.5 °C) for the near future (2020–2050) (Zhou et al., 2013). Meanwhile, daily mean temperatures across the Lancang River Basin are projected to be higher during dry seasons (7.5–10.5 °C) than during wet seasons (6.0–7.5 °C) under the 6 °C warming scenario. Furthermore, the warming trend is expected to extend to higher elevations, especially above 400 m, in the Mekong River Basin during this century (Zhou et al., 2013).

3.5.1.2 Uncertainty in Estimated Past and Projected Future Precipitation

Previous studies have reported moderately increasing trends in annual precipitation over the Lancang-Mekong River Basin (LMRB) in recent decades, although with varying levels of confidence (Lacombe et al., 2013). One recent study found a wet but statistically insignificant trend of 24.8 mm/decade in annual precipitation over the LMRB during the period 1983–2016 (Chen et al., 2019). In contrast, from 1981 to 2007, annual precipitation based on daily gridded (0.25° × 0.25°) APHRODITE (Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources) data showed a significant increasing trend of 52.6 mm/decade over the Mekong River Basin (Lutz et al., 2014). Similarly, there was a significant increase (14.5 mm/decade) in annual precipitation over the Lancang River Basin during the period 1981–2010, based on in situ precipitation records at seven meteorological stations (Liu et al., 2022). These findings suggest that while there are differences in estimates based on different datasets, there has been an increasing trend in annual precipitation in the LMRB in recent years. There is a consensus, with high confidence, that significant increases in annual precipitation are expected across the LMRB over the next 30–50 years (Lacombe et al., 2012). Variability in annual precipitation is also projected to increase in this basin (Lauri et al., 2012). This high confidence in projected wetting trends is primarily attributed to future global warming, which is likely to enhance the transport of water vapor from the Indian Ocean and the western Pacific Ocean towards the LMRB, resulting in increased precipitation across the region (Zhang et al., 2017). Depending on the emissions scenario, these projected wetting trends in annual precipitation over the Lancang-Mekong River Basin range from 2.5–8.6% to 1.2–5.8% per year. For instance, annual precipitation is expected to increase by 35–365 mm (3–14%) over the Mekong River Basin by 2050 (Zhou et al., 2013) and by approximately 10% over the Lancang River Basin under the 2 °C warming scenario.

In terms of monthly precipitation, projections indicate increases over the Lancang River Basin for all months by 20–60% under warming scenarios of 2–6 °C, except for April, which shows a projected decrease of 16–40% (Kingston et al., 2011). With moderate confidence, it is expected that precipitation will increase during the wet season (May–October) over the Mekong River Basin by 2050 but decrease in the dry season (November–April) (Zhou et al., 2013). Additionally, there is a likelihood that precipitation will shift from higher to lower elevations, such that historical annual precipitation levels of 1,500 mm recorded at an elevation of approximately 280 m may be observed at elevations of around 80 m (Zhou et al., 2013) (Fig. 3.33).

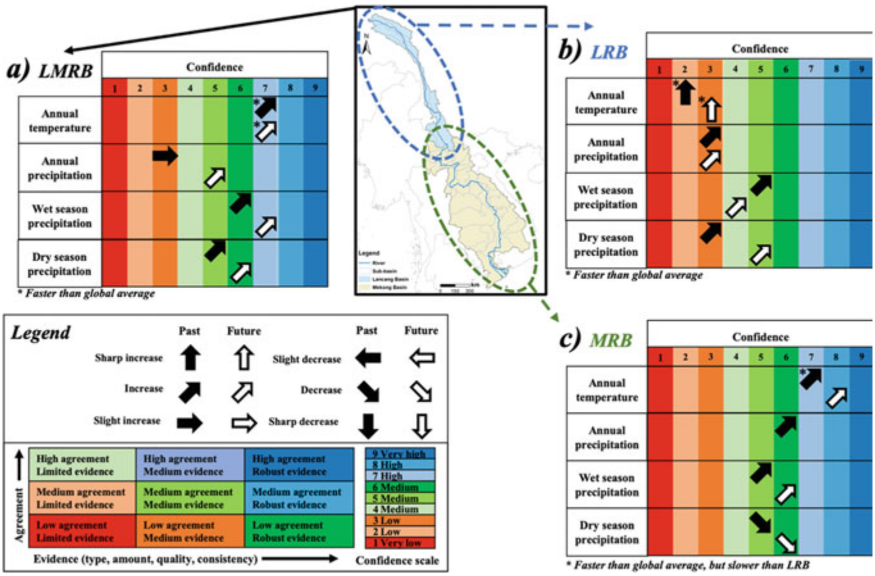

Fig. 3.33 Changes in temperature and precipitation over the **a** LMRB, **b** upper part of the LMRB (LRB) and **c** lower part of the LMRB (MRB), based on the published literature

3.5.2 Water Resources in the LMRB: Historical Changes and Future Projections

3.5.2.1 Annual Mean Discharge

A general trend of decreasing annual streamflow was identified in the Lancang-Mekong River Basin (LMRB) over the period of 1960–2010, although this trend is associated with low confidence. However, no clear trend has been observed after 2010 (Ruiz-Barradas et al., 2018). It's worth noting that different studies have reported varying trends in historical streamflow in the LMRB, with some indicating a decrease and others suggesting an increase. These discrepancies can be attributed to differences in data sources and methodologies used in each study.

The changes in streamflow in the LMRB are the result of a combination of climate change and human activities, and the contributions of these factors vary across regions and time periods. Climate change was a dominant driver of streamflow alterations in the LMRB before 2010, accounting for 82.3% of the changes during the transition period of 1992–2009. In contrast, human activities, primarily dam construction, played a more significant role after 2010, contributing 61.9% of the changes in streamflow during the post-impact period of 2010–2014 (Li et al., 2017). Notably, the hydrological response of the Lancang River Basin appears to be more sensitive to climate factors than human activities when compared to the Mekong River Basin, underscoring the increasing impact of intensive human activities on hydrological processes in the Mekong River Basin, particularly in recent years (Shin et al. 2020).

Projections for future streamflow changes exhibit spatial variability, particularly within the Mekong River Basin (Liu et al., 2022). While an increasing trend in streamflow is anticipated for the Lancang-Mekong River Basin, significant uncertainties persist. Some studies project a 21% increase in annual runoff by the 2030s compared to the historical period (1951–2000) based on 11 global climate models (GCMs) (Eastham et al., 2008). In contrast, Västilä et al. (2010) reported only a 4% increase in annual flow by the 2040s in the Lancang-Mekong River Basin, using dynamically downscaled data from the ECHAM4 climate model. Other investigations based on CMIP5 datasets for the near future (2036–2065) have also indicated relatively small changes in mean annual flow, ranging from 3 to 10% in the Lancang-Mekong River Basin (Hoang et al., 2016; Västilä et al., 2010).

Furthermore, the magnitude and frequency of extremely high-flow events are projected to increase, while low-flow events are expected to occur less frequently, particularly as a result of climate change (Hoang et al., 2016). These more frequent extreme high-flow events could pose increased flood risks in the Lancang-Mekong River Basin. It's worth noting that the extensive construction of hydropower projects, which has led to changes in discharge, is anticipated to have a more significant impact on hydrography in the basin compared to climate change over the next 20–30 years (Hoang et al., 2019; Lauri et al., 2012) (Fig. 3.34).

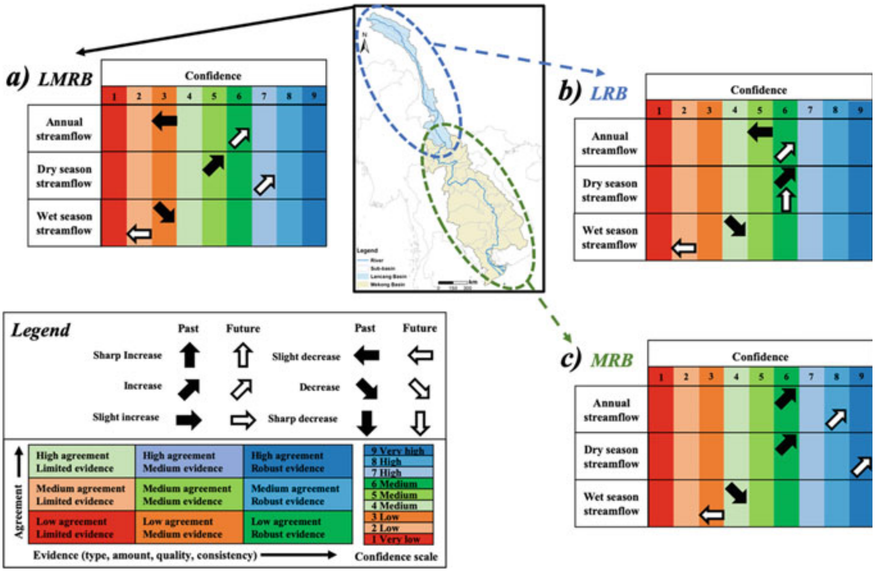

Fig. 3.34 Changes in streamflow over **a** the LMRB, **b** LRB, and **c** MRB, based on published works

3.5.2.2 Groundwater

Global groundwater data from the International Groundwater Resources Assessment Center (IGRAC) indicate that approximately 0.55 km^3 of groundwater was extracted from the Lancang-Mekong River Basin (mainly from the Mekong River Basin) in 2000 (Wada et al., 2010). However, it's important to note that this estimate is significantly lower than what has been reported by country-based statistics (Ha et al., 2015). This discrepancy could be attributed to the fact that the global database from IGRAC may not fully account for groundwater use by individual households across the basin (Pokhrel et al., 2018a, 2018b).

The groundwater system in the Lancang-Mekong River Basin (LMRB) is primarily influenced by changing hydrological conditions and intensive human activities, both of which impact the groundwater balance in terms of recharge and withdrawal (White, 2002). Over a 30-year monitoring period in the Mekong Delta, a significant decline in groundwater levels has been observed (IUCN, 2011). Particularly in Ca Mau Province, Vietnam, groundwater levels have dropped by as much as 10 m since 1995 (IUCN, 2011). In the river delta region of Vietnam, groundwater levels have consistently decreased at a rate of approximately 0.3 m per year, as documented by data from nested monitoring wells. This decline in groundwater levels has also led to land subsidence in the region, occurring at an average rate of about 1.6 cm per year (Erban et al., 2013).

The principal factors driving these declining trends in groundwater levels can be attributed to increased water demand and reduced water supply (IUCN, 2011). The growing population and expansion of agriculture have generated a higher demand for freshwater resources, intensifying the exploitation of groundwater. Additionally, the supply of clean water in this region has decreased (IUCN, 2011). Reduced groundwater recharge is primarily a result of changes in land use, including deforestation and increased cultivation of fields, which reduce the groundwater recharge ratio accordingly (White, 2002).

3.5.2.3 Potential Environmental and Social Impacts of Water Resource Changes

Anticipated changes in the water resources of the Lancang-Mekong River Basin (LMRB) are likely to have significant implications for sustainable water management. These projected changes in the basin's flow regime are expected to have negative consequences across several dimensions.

Firstly, substantial alterations to flow regimes can disrupt aquatic ecosystems by changing the distribution of vegetation, the natural habitats of native species, and fish migration patterns (Arias et al., 2012). Dams, in particular, are expected to profoundly impact fish abundance and catch in the lower reaches of the Mekong River Basin, which can have implications for dietary protein consumption (Burbano et al., 2020). Furthermore, reduced streamflow during the wet season may impede overland water flows that trigger the natural sedimentation process on floodplains, affecting flood-recession agriculture. Decreased sedimentation will also reduce the nutrients carried by sediment during flood events, further impacting crop yields (Hoang et al., 2019).

It is projected that water use in the LMRB will significantly increase due to rapid socioeconomic development and population growth, outpacing the increase in available water resources (Eastham et al., 2008). This could lead to growing challenges related to water security, with an increasing number of people facing water stress. Moreover, studies have shown that regions with significantly regulated flows due to dams tend to experience downstream shifts in water scarcity hotspots (Veldkamp et al., 2017).

The demand for groundwater in the LMRB is expected to surge under climate change conditions, as surface water becomes less accessible. This intensification of groundwater extraction could lead to large-scale land subsidence, potentially resulting in the release of arsenic from deep groundwater through vertical migration (Wagner et al., 2012). This poses risks to crop yields and human health in the future (Merola et al., 2014).

Despite these negative effects of an altered water system, there are some positive impacts to consider. For instance, an increase in streamflow during the dry season (Shin et al., 2020) could help alleviate water stress for agriculture (Son et al., 2012). Higher water levels during the dry season can prevent saltwater intrusion downstream, particularly in the vulnerable Mekong Delta (Smajgl et al., 2015). Additionally, the relatively lower water levels during the wet season induced by dams imply reduced flood risks along the river, especially in the main floodplains of the Mekong Delta (Pokhrel et al., 2018a, 2018b).

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Chapter 4
Arsenic in Hydro-geo-biospheres of the Mekong River Watershed: Implications for Human Health

Yan Zheng, Bin Xu, Jingyu Liu, Yating Shen, Kongkea Phan, and Benjamin C. Bostick

Abstract This chapter assesses human health risks of inorganic arsenic (As) from drinking well water and consumption of rice irrigated by high-As groundwater in the Mekong River Delta. Geogenic inorganic As (iAs) occurring at elevated levels in groundwater has been detected in more than 70 countries. Among mostly rural residents relying on groundwater for drinking, this exposure has resulted in negative health consequences including visible skin lesions, multiple internal organ cancers, numerous invisible non-cancer health effects such as cardiovascular diseases, and premature deaths. In the Mekong River Delta (MRD, defined by elevation <10 m above sea level in this book), As issues in groundwater have been documented as early as 1999 in Cambodia, with literature reporting its occurrence in Vietnam since 2005. Since the early 2000s, efforts have been made to test for As in

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about 100,000 wells from Cambodia, Laos, Vietnam and Thailand. Here, a combined dataset with a total of 94,768 unique As tests was analyzed to illustrate the spatial patterns and to assess the health risks of drinking well water As in Cambodia and in southern Vietnam. Although knowledge is far more limited, an attempt was also made to examine the potential health risks associated with iAs exposure from rice, a major staple for the MRD. Here, irrigation using highly As enriched groundwater for rice cultivation has expanded this environmental health problem from the hydrosphere (water) to the geosphere (soil) and, in turn, the biosphere (rice, and ultimately humans). Of 41,928 tests in Cambodia, 35.8% exceeded 10 μg/L, the WHO guideline value for drinking water As, while 21.5% exceeded 50 μg/L, the Cambodian drinking water standard. Of 52,858 tests in Vietnam, the exceedance rate for 10 μg/L, which is also the Vietnamese drinking water standard, is 10.0%. High As wells, regardless of whether it is relative to 10 or 50 μg/L, are located in proximity to the main course of the Mekong-Bassac Rivers, especially within a 5 km distance. The vast majority (>98%) of high-As wells are located in low-lying areas, i.e. <25 m elevation in Cambodia and <10 m elevation in Vietnam. High-As wells occur frequently at shallow depths (<70 m) across the MRD but also at deeper depths (300–500 m) in Vietnam. Due to the clustering of high As wells along the Mekong-Bassac Rivers, extreme human health tolls are identified in 11 districts of Cambodia and 3 districts of Vietnam with a population attributable fraction exceeding 0.1, meaning that >1 in every 10 adult deaths is solely due to drinking water As exposure. **The annual excess deaths attributable to arsenic exposure alone is 1204 in Cambodia and 1486 in Vietnam, or 1 in every 27 adult deaths and 1 in every 78 adult deaths, respectively. In addition to uncertainties in bioavailability and toxicity of iAs in rice grains, soil and rice As data, especially rice As speciation data needed for risk assessment, are still limited in the MRD**.

4.1 Geogenic Arsenic in Groundwater of Southeast Asia

4.1.1 Groundwater Quality Surveys in Cambodia, Laos and Vietnam

The Mekong River flows south from the northern hills (elevation up to 1000 m) before it enters the low-lying (elevation <10 m) flood plains referred to here as the Mekong River Delta (Fig. 4.1). Occupying much of southern Cambodia (upper MRD 10,000 km^2) and southern Vietnam (lower MRD 52,000 km^2) with an area of 62,000 km^2, the Mekong River Delta (MRD) is one of the largest deltas in Southeast Asia inhabited by about 8 million Cambodians and 25 million Vietnamese (Fig. 4.1). The topographic features of the Mekong River Watershed resulted from tectonic uplift and folding caused by the collision of the Indian and Eurasian tectonic plates around 50 million years ago (Lap Nguyen et al., 2000). The climate in the MRD is tropical, with average annual temperatures of 27–30 °C. The monsoonal rainy season lasts

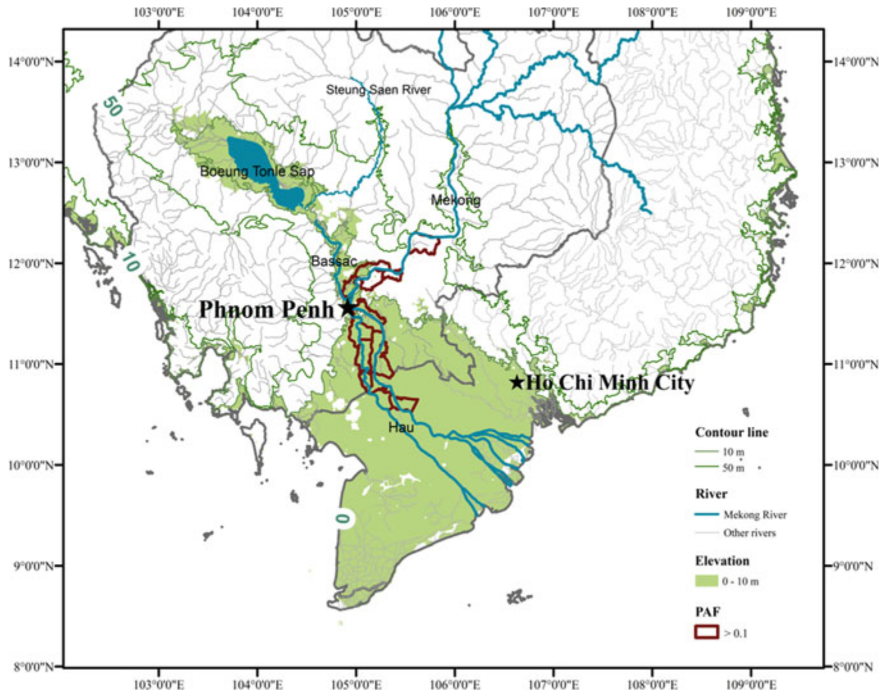


Fig. 4.1 Map of the Mekong River Delta (MRD). The elevation contour lines of 10 and 50 m are shown in green, with the MRD region defined by <10 m elevation, with the national border between Cambodia and Vietnam separating the upper and lower MRD. Extensive river networks are also shown. 11 Districts in Cambodia and 3 districts in Vietnam with high arsenic health risks, defined by Population Attributable Fraction (PAF) values >0.1 (see Table 4.4 for details), are highlighted in dark red outline

from April to November (Husson et al., 2000). The mean annual precipitation ranges from 2400 mm in the west to some 1500 mm in the center and east.

Since the mid-1990s, groundwater in the MRD of southern Vietnam has been utilized for domestic use by private household tube-wells. Arsenic (As) contamination of groundwater in the MRD appeared first in literature in 2005 (Stanger et al., 2005). Since 2007, surveys and assessments of As groundwater contamination have been conducted in the region (Fig. 4.2a). The first survey of groundwater (n = 405) was carried out in 2007 in 4 provinces, An Giang, Dong Thap, Kien Giang and Long An, all located in the MRD (Hoang et al., 2010). About half of the groundwater samples collected from An Giang and Dong Thap Provinces contained arsenic concentrations higher than the WHO and the Vietnamese national guideline level of 10 μg/L. Further, that arsenic level in groundwater having distinct spatial patterns was already noted, with distance to the Mekong River and the depth of wells playing significant roles. This provided the first clue suggesting that the Mekong River plays an important role in groundwater arsenic occurrence. In Vietnam, a National Groundwater Monitoring Network for the South (NGMNS), which has been installed since the 1990s, is used to monitor groundwater quality in the MRD. The geochemical dataset for NGMNS wells collected by the Division of Water Resources Planning and Investigation of the South of Vietnam from 1994–2014 showed an exceedance rate of 13.8% relative to Vietnam's national drinking water quality standard of 10 μg/L, with an average value of 8.5 μg/L. High As concentrations (>100 μg/L) are mostly observed in shallow wells (<60 m) (Ha et al., 2019). This trend is also evident in a 3-dimensional map to illustrate the distribution of As concentrations by analyzing 53,000 groundwater As concentration data of the Department for Water Resources Management in Vietnam (Erban et al., 2014). In this large dataset, 10.5% of samples exceed the WHO drinking water guideline value for arsenic at 10 μg/L. It appears that the arsenic issue is most severe in An Giang and Dong Thap Provinces, which are located near the Mekong River.

In Cambodia, unsafe levels of As in shallow groundwater were first documented in 1999 in an unpublished report by the Japanese International Cooperation Agency (JICA), submitted to the Cambodian Ministry of Rural Development (Phan et al., 2010). Consequently, the Ministry of Rural Development organized a national drinking water quality assessment in 13 provinces of Cambodia through a close collaboration of local authorities, research teams and non-governmental organizations (NGOs). Seven provinces in Cambodia were found to have high levels of arsenic in the groundwater. Out of a total of 47,950 wells tested nationally, 30,839 wells were from these 7 provinces and were tested for arsenic by field test kits between 2005 and 2009 (Phok et al., 2018). Up to 35–38% of the tested wells contained arsenic at levels above the WHO guideline value of 10 μg/L and the Cambodian National Standards of 50 μg/L. The occurrence of elevated arsenic in groundwater varies greatly in different watersheds, with only about 2.8–3% of wells along the Stung Saen River in Kampong Thom containing >50 μg/L As while the exceedance rate is 50% on the lower floodplains of the Mekong and Bassac Rivers in Kandal province. An NGO, the Resource Development International—Cambodia (RDI), has also tested over 10,000 wells as part of its programme to assess water quality across Cambodia. Groundwater arsenic is found to be most frequently occurring in parts of Kandal, Kampong Cham, and Prey Veng provinces (Fig. 4.2a).

Unlike Cambodia and Vietnam, survey data are fewer and less available for the MRD region of the Lao PDR. In 2001, UNICEF organized testing of approximately 200 wells of suspected risk areas within the provinces of Attapeu, Savannakhet, Champassak and Saravan (Kim et al., 2011). Some samples have arsenic levels above the WHO guideline of 10 μg/L and only one of them had arsenic concentrations of 112 μg/L, which exceeded the 50 μg/L drinking water standard proposed and later adopted by Lao PDR. Approximately 680 tube-well water samples taken from the Holocene aquifer in the Mekong valley areas were tested in 2004 through campaigns initiated by UNICEF, with support from the government of Lao PDR and the Adventist Development and Relief Agency (Kim et al., 2011). Results showed that 21% of all samples had arsenic concentrations exceeding the WHO guideline value for drinking water of 10 μg/L while 1% exceeded the national standard of 50 μg/L. In 2008, a total of 61 tube-well water samples were also collected from Vientiane, Bolikhamxai, Savannakhet, Saravane, Champasak and Attapeu. The concentrations ranged from <0.5–278 µg/L, with over half exceeding the WHO guideline of 10 µg/L (Chanpiwat et al., 2011).

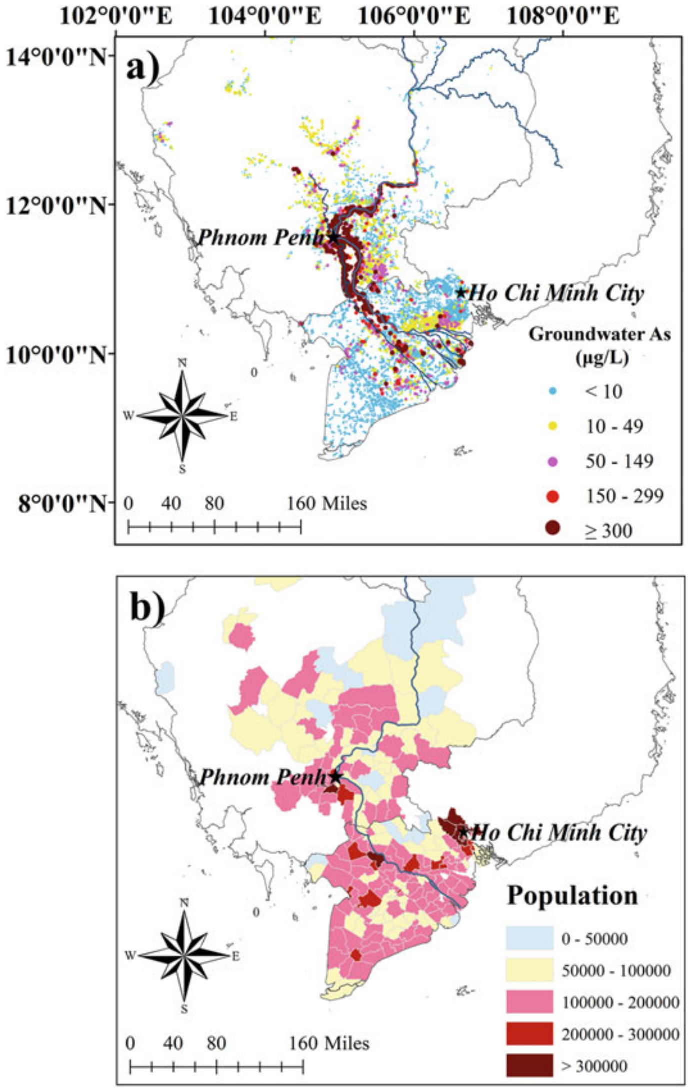
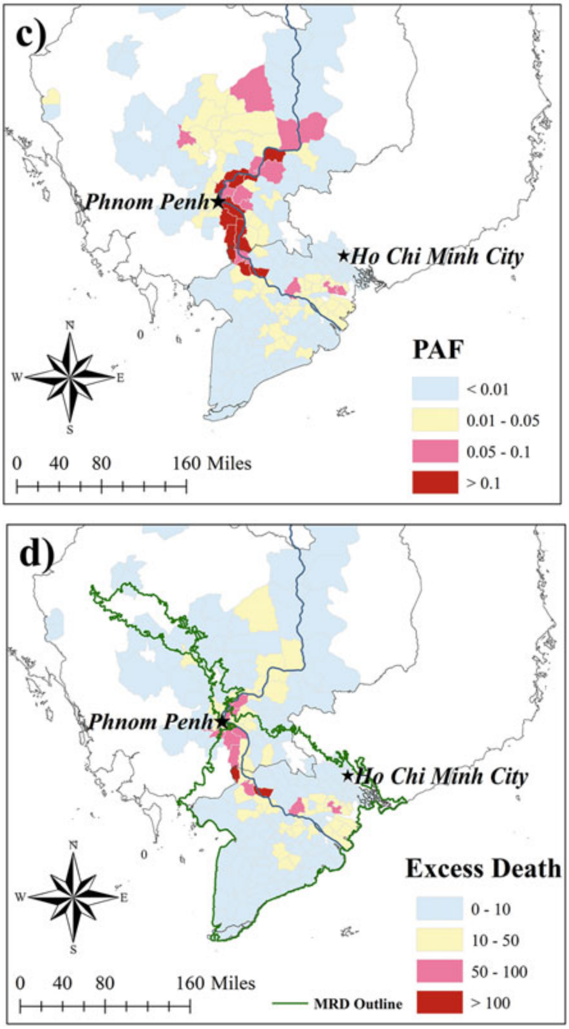


Fig. 4.2 Health effects of groundwater arsenic exposure in the Mekong Delta encompassing Cambodia and Vietnam. **a** Concentration of individual well water arsenic based on 41,928 unique tests from Cambodia (the National Well Database) and 52,858 tests from Vietnam (the Department of Water Resources Management). **b** Population from General Population Census of the Kingdom of Cambodia 2019 and Completed Results of the 2019 Vietnam Population and Housing Census mapped to administrative district. **c** Population Attributable Fraction (PAF) distribution, and **d** excess deaths. The MRD area (<10 m elevation) is outlined in green

Fig. 4.2 (continued)



4.1.2 Arsenic in Groundwater of Thailand

Although Thailand is not located in the MRD, a brief description is included to provide a fuller account of arsenic issues in Southeast Asia. Arsenic has never been found to occur naturally in groundwater in Thailand (Kohnhorst, 2005). Tin mining, or transportation and deposition of arsenic-rich erosion products from elevated areas to downgradient regions, was suggested as the cause of pollution (Kohnhorst, 2005). Ron Phibun District, a well-known area affected by arsenic, has more than a century long history of mining (Fordyce et al., 1995). Abundant arsenopyrite and pyrite, cassiterite and wolframite mineralization occurs widely in pegmatites and geissenized quartz-vein margins throughout the Khao Luang batholith (Fordyce et al., 1995). In 1994, a collaborative study between Thai and British government authorities revealed that arsenic contamination of shallow groundwater ranged between 1.25 and 5,114 μg/L (Kim et al., 2011). Additionally, about 69.6% of the 23 shallow wells contained arsenic concentrations exceeding the WHO guideline for drinking water (10 μg/L). About 15,000 villagers were estimated to be at risk when the problems were first recognized, with over 1000 recorded cases of skin disorders directly attributable to chronic arsenism (Fordyce et al., 1995). As a result, mining ceased, with remediation measures such as the removal of mine waste for disposal at confined local landfills implemented (Wattanasen et al., 2006).

4.2 Health Effects Due to Exposure to Drinking Water As in Cambodia and Vietnam

4.2.1 Rationale for Assessment

A few high-income countries have moved towards adopting drinking water quality standards for As to levels below the WHO guideline value of 10 μg/L (Zheng, 2020). This is because new health evidence suggests that even 10 μg/L may not be protective enough for human health, especially during early, biologically vulnerable stages of life (NRC, 2013). It is worth noting that the WHO guideline value is provisional, and is a recommendation based on treatment performance and analytical achievability. It is possible for these same practical reasons that countries in the MRD region, except for Vietnam, still use 50 μg/L as their national standard, so meeting such standards clearly does not mean "safe". In the following assessment of health effects, we therefore consider exposure to As greater than 10 μg/L as the "exposed" groups whereas those below as the "reference" groups.

Many epidemiological studies have pointed out that chronic inorganic As exposure via drinking water is associated with mortality caused by many diseases, including lung, skin and bladder cancers, carotid atherosclerosis, hypertension, ischemic heart diseases and skin lesions (NRC, 2013). Due to the latency effect, the disease symptoms usually take years to develop. An important non-cancer disease outcome is cardiovascular disease, one of the major causes of death (Wang et al., 2007). A dose–response relationship has been demonstrated between the level of exposure to As in well water and mortality from ischemic heart disease in a large Bangladeshi cohort (Chen et al., 2011). Regardless of the exact cause of death for each As exposed individual, two studies have reported dose–response relationships between drinking water As levels and mortality rates established based on 115,903 (Sohel et al., 2009) and 11,746 subjects in Bangladesh (Argos et al., 2010). Taking advantage of such well characterized dose–response in mortality among local populations, Flanagan et al. (2012) conducted a health effect assessment that is based also on a careful evaluation of exposure to As using data (n = 14,442) from a national drinking water quality survey of Bangladesh, concluding that 1 in every 18 adult deaths is attributable to chronic As exposure alone.

Although the exposure to drinking water As in the MRD regions of Cambodia and Vietnam has begun as early as the mid-1990s (Berg et al., 2001) due to rural residents' reliance on private tube-wells, there has never been a quantitative assessment of health effects. Because groundwater quality surveys have revealed considerable heterogeneity in arsenic spatial distribution (Fig. 4.2a), the assessment of exposure and health effects makes an effort to address this feature.

4.2.2 Methods

Here, we adopt methodologies described in Flanagan et al. (2012) to estimate excess deaths using the aforementioned dose–response relationship (Sohel et al., 2009), with modifications described as follows.

Excess death (ED). Mortality rate describes the frequency with which deaths are occurring in a given population over a given time period (for chronic disease, a time duration of 1 year is frequently used). If these are higher than the expected mortality rate in non-crisis or normal conditions in that population, then the difference between the mortality rate under normal and crisis conditions represents the "excess". For a given time period and a given population size, we can estimate the number of excess death (ED) due to a specific crisis. Thus, the ED describes the mortality attributable to a *specific* reason, and in our case, chronic exposure to drinking water As, that would have been zero normally without exposure. We recognize that the influence of As on human health is systematic and multifaceted. Therefore, when the relationship between the dose and a disease outcome is available, it is also desirable to evaluate the health effects of that disease. As the first step, it is justified to evaluate ED because it can reflect the overall impact and to indicate the severity of human health toll attributable to As exposure.

Population Attributable Fraction (PAF). To estimate the number of excess deaths in each geopolitical district in the MRD, the population attributable fraction (PAF) can be used. Specifically, it is defined as the fraction measuring how much of the health burden in a population could be eliminated if there had been no exposure (Mansournia & Altman, 2018), as in Eq. (4.1) below:

$$PAF = \frac{O - E}{O} \tag{4.1}$$

where O is the **Observed** number of cases, and E is the **Expected** number of cases under no exposure.

For a region of interest with a total population of N, the proportion of the population in four groups representing reference group (10 μg/L), i.e., low (10–49 μg/

L), medium (50–149 μg/L) and high (≥150 μg/L) exposure groups, is expressed as $1 - p_1 - p_2 - p_3$, p_1, p_2, p_3, respectively (Table 4.1). The reference group is chosen on the basis of the WHO guideline value of 10 μg/L for arsenic in drinking water. Given the mortality rate q of the reference group and relative risk (RR_i) for different levels of exposure, the number of deaths of low, medium and high exposed groups can be estimated (Table 4.1). Thus, the PAF equation is rewritten by replacing O and E with their corresponding values for the three exposure groups in Eq. (4.2) as follows:

$$PAF = \frac{\sum p_i(RR_i - 1)}{\sum p_i(RR_i - 1) + 1} \tag{4.2}$$

For ease of calculation, we approximate the relative risk values (RR_i) by hazard ratios of non-accidental deaths from Sohel's 2009 study. The proportion of the population for the low, medium, and high exposure groups is taken as the same as the proportion of wells for the corresponding As intervals (Table 4.1). Substituting these two terms to Eq. (4.2), the PAF is calculated using Eq. (4.3) below:

$$PAF = \frac{\sum p_{(well)i}(HR_i - 1)}{\sum p_{(well)i}(HR_i - 1) + 1} \tag{4.3}$$

From these resulting PAF values, the annual number of deaths for any geopolitical district (Table 4.1, last row) is estimated by using the area's population (N) multiplied by the area's crude death rate (CRD, q in Table 4.1), i.e., the number of deaths in 1000 people in any given year, usually available through each country's Health Ministry. The crude death rate summarized by the Department of Economic and Social Affairs, United Nations, which is listed in World Population Prospects 2019, is used here. The CDR values used are 6.0 and 6.3 per 1000 people for Cambodia and Vietnam from 2015 to 2019, respectively. The sum of the number of deaths for the low, medium and high exposure groups is taken as the ED attributable to As exposure.

Table 4.1 Terms used in PAF and ED calculations

Group[a]	Reference	Low	Medium	High
Arsenic concentration in well water (μg/L)	<10	10–49	50–149	≥150
Population proportion	$1 - p_1 - p_2 - p_3$	p_1	p_2	p_3
Mortality rate (per year)	q^b	qRR_1	qRR_2	qRR_3
No. of deaths (per year)	$N(1 - p_1 - p_2 - p_3)q$	Np_1qRR_1	Np_2qRR_2	Np_3qRR_3

[a] The reference, low, medium and high groups are chosen to correspond to the reported hazard ratios of non-accidental death by Sohel et al. (2009), and are 1.00, 1.16, 1.26 and 1.36, respectively
[b] q represents the crude death rate, i.e., the number of deaths in 1000 people in any given year, usually available through each country's Health Ministry

Dataset. Data used for estimation are from diverse sources. In the following, the population and water arsenic datasets are described.

Population data: In Cambodia, the national census was conducted in 1962, 1998, 2008 and 2019 respectively by the National Institute of Statistics. The final census report has population size, trends in fertility, mortality, migration and disability etc. by geopolitical units of Province, District and Commune (Some special indexes are only provided within the province range). Here, the adult population of each district in 2019 is calculated by the population in each district multiplied by the percentage of the population aged 15 years or older because the percentage of those aged 18 years or older is not available. In Vietnam, the demographic information is obtained from the Completed Results of the 2019 Viet Nam Population and Housing Census. This was the fifth Population and Housing Census since the country's reunification in 1975. Similarly, each district's population and age ratio are offered as part of the 2019 census results. Adults are also defined as people aged 15 years and above with the number of each district estimated by multiplying the national age ratio and the number of people living in each district.

Arsenic data: The Ministry of Rural Development of Cambodia and UNICEF developed and administered an As well water testing database primarily based on extensive As testing by Research Development International (RDI), an NGO. Well depths of sample wells were also recorded. In addition, a Tonlé Sap Rural Water Supply and Sanitation Project financed by the Asian Development Bank (ADB) provided information on additional hydrochemical parameters (arsenic, iron, chloride etc.) and coordinates (latitude and longitude). In the end, the dataset consists of 42,567 arsenic records of investigated wells sampled between 1997 and 2009 in Cambodia. In Vietnam, the Department of Water Resources Management constructed a database that includes the well depth, year of well installation, coordinates and the arsenic concentration. They shared with researchers 52,858 arsenic concentration data points (Erban et al., 2014) collected from 1907 to 2008. The dataset also includes the coordinates (latitude and longitude), well depth, installation year, and the arsenic concentration. It is noted that because of technical limitations of field testing kits, although discrete values are given for some As measurements, they are not exact values but represent a possible range of values. However, misclassifications remain rare relative to 10 μg/L (He et al., 2022).

The original data of Cambodia has a total of 42,567 well arsenic records from various database sources with columns including well ID, WGS coordinates, sample date, well depth and several water chemical parameters (chloride, iron, manganese etc.). The province, district, commune, and village of each well are also documented, although a fraction of this documentation does not match the attribution from the WGS coordinates. Here, the geopolitical district of each well is assigned only by its WGS coordinate. Furthermore, duplicate data and multiple arsenic values for one well exist. To make sure that every well has its unique value that best reflects reality, data are "cleaned" using rules as follows: (1) If multiple arsenic values of one well exist, the well is removed from the dataset if As values are distributed in more than one classification group stated in Table 4.1. The reason for doing this is that we do not want the screening or data entry errors to be a source of variance of calculated PAF values. This process eliminated 64 data points of 30 wells; (2) If multiple arsenic values of one well exist only in one classification group, then the value with the latest sample date is kept and used for analysis; this process eliminated 150 data points. We have noted that there are 1,119 wells with the same WGS coordinates, although their well depths and As values are different, suggesting that the testing was done in a village or commune though without GPS measurements to determine the exact latitude and longitude of the tested well. In addition, these wells have been assigned a unique well ID thus it is justified to recognize them as different wells so they are not removed from the database. After this exercise, a dataset of 41,928 wells with their unique As values is used for analysis. Fortunately, the dataset from southern Vietnam has been cleaned by Erban et al. (2014). The summary statistics of well water arsenic datasets can be found in Table 4.2.

Spatial Analysis by Geographic Information System. A total of 241 administrative districts with 94,786 records of arsenic concentrations of wells in the Mekong Delta are used for spatial analysis using ArcGIS 10.6. Colour-coded maps generated by ArcGIS are used to illustrate the varying degrees of severity of health risks for each district, in addition to showing the individual well water As data classified to 5 groups from cold to warm colours: ≤10, 10–49, 50–149, 150–299, ≥300 μg/L (Fig. 4.2).

Well water arsenic concentrations are classified based on the well's elevation, its distance to a major river and the depth (Table 4.3; Figs. 4.3, 4.4 and 4.5). Because most of the high arsenic points are located along the main course of the Mekong that includes the Bassac River after the Mekong bifurcates to two major branches in Phnom Penh (Fig. 4.1), a distance analysis was performed in ArcGIS to explore the relationship between the concentrations of As of each well and their locations relative to the Mekong or the Bassac River. It is noted that there are also high arsenic wells near the Steung Saen River, a major tributary of Tonlé Sap. Therefore, in order to distinguish this smaller river from the Mekong and the Bassac, data points ($n = 1439$) within districts of Kampong Svay, Krong Stueng Saen, Prasat Sambour and Sandan in the province of Kampong Thom are analysed using the well's distance to the Steung Saen River. A total of 38,866 data points, from the following 10 provinces of Kampong Cham, Kampong Chhnang, Kratie, Kampong Speu, Takeo, Svay Rieng, Tboung Khmum, Kandal, Phnom Penh and Prey Veng are included in the distance analysis to the main course of the Mekong, including the Bassac south of Phnom Penh. Wells ($n = 1{,}623$) located in the northern and western most part of Cambodia, far away from the Mekong-Bassac river influence, are excluded so the number of points is less than 41,928. All data points in Vietnam are used. A tool of 'Generate near table' in ArcGIS was used to calculate distance and other proximity information between features in one or more feature class or layer. In our analysis, distance from a well to the river is defined as the two-dimensional Euclidean distance. Only the nearest tributary to any given well is used for calculation. Therefore, every well has its unique distance value.

For PAF and ED estimations, the smallest spatial unit that the analysis can be performed is each administrative district. This is because the population within each

Table 4.2 Summary statistics of Well Water As data in Cambodia and southern Vietnam

Country	No	Database source	[As] median (µg/L)	[As] mean (µg/L)	[As] max (µg/L)	%Wells [As] > 5 µg/L (%)	%Wells [As] > 10 µg/L (%)	%Wells [As] > 50 µg/L (%)
Cambodia	41,928	RDI DWQI Database; UNICEF Arsenic Database; TSRWSSP Well Database; World Vision Database; MRD Well Database	10.0	58.8	2500	54.9	35.8	21.5
Vietnam	52,858	The Department of Water Resources Management	0.0	14.5	1470	14.7	10.0	4.9

Table 4.3 Distribution of well water [As] by elevation, distance to the closest major river and the depth of each well in Cambodia and southern Vietnam

Location		Distance	No	Area (km^2)	[As] (µg/L)			%Wells with [As] > a threshold value		
					Median	Mean	Max	>5 µg/L (%)	>10 µg/L (%)	>50 µg/L (%)
Cambodia	Elevation	**≤10 m**	19,385	22,355	10.0	84.4	1000.0	60.7	42.0	28.4
		0–3	265		0.0	70.7	500.0	47.9	36.6	27.2
		3–6	5365		10.0	81.9	1000.0	58.6	39.0	26.6
		6–10	13,755		10.0	85.6	1000.0	61.7	43.2	29.2
		>10 m ≤25 m	19,004	29,737	10.0	43.0	2500.0	56.3	34.9	18.3
		>25 m ≤50 m	2286	20,674	0.0	4.87	500.0	20.0	9.6	1.2
		>50 m	1253		0.0	1.23	100.0	7.4	1.8	0.16
	Distance (Mekong river or Bassac River)	**≤25 km**	35,576		10.0	67.9	2500.0	58.7	40.0	25.1
		≤5	22,564		25.0	97.1	2500.0	70.5	52.3	36.2
		5–10	5944		0.0	25.2	1000.0	46.7	23.3	8.1
		10–15	3342		0.0	13.2	500.0	38.9	18.3	4.7
		15–20	2175		0.0	10.2	500.0	28.9	13.6	3.9
		20–25	1551		0.0	5.0	500.0	17.8	7.0	1.5
		>25 km	6352		0.0	7.7	500.0	33.7	12.7	1.7
	Depth	**≤25 m**	9816		0.0	33.6	1000.0	43.5	25.6	11.8
		>25 m ≤50 m	26,919		10.0	61.8	2500.0	57.1	37.4	23.4
		>50 m ≤75 m	4083		10.0	90.9	1000.0	66.9	48.4	30.9

(continued)

Table 4.3 (continued)

Location		Distance	No	Area (km^2)	[As] (µg/L)			%Wells with [As] > a threshold value		
					Median	Mean	Max	>5 µg/L (%)	>10 µg/L (%)	>50 µg/L (%)
		>75 m	107		10.0	71.2	750.0	47.7	22.4	14.0
Vietnam	Elevation	**≤10 m**	52,281	43,985	0.0	14.6	1470	14.9	10.1	4.9
		0–3	31,395		0.0	8.5	900	13.5	8.4	3.0
		3–6	18,347		0.0	21.2	1470	16.3	11.8	6.8
		6–10	2539		0.0	42.4	1380	20.6	18.2	15.1
		>10 m	577	7034 (10–50 m)	0.0	1.0	100	1.6	0.9	0.3
	Distance (Mekong river or Bassac river)	**≤25 km**	33,239		0.0	22.1	1470	21.2	14.8	7.4
		≤5	14,788		0.0	37.2	1470	24.2	18.7	12.5
		5–10	8044		1.0	14.4	1070	21.3	14.2	4.6
		10–15	4719		2.0	8.0	500	20.5	11.6	2.7
		15–20	2817		0.0	5.7	500	13.1	8.2	1.8
		20–25	2871		0.0	5.1	500	14.7	8.2	1.7
		>25 km	19,619		0.0	1.6	500	3.7	1.8	0.6
	Depth	**≤50 m**	20,029		0.0	27.4	1190	15.8	12.9	9.6
		>50 m ≤100 m	20,568		0.0	7.7	1470	12.8	6.8	2.5
		>100 m ≤200 m	7469		0.0	2.8	500	5.9	2.9	0.9
		>200 m	3489		1.0	8.9	500	34.9	26.1	1.5

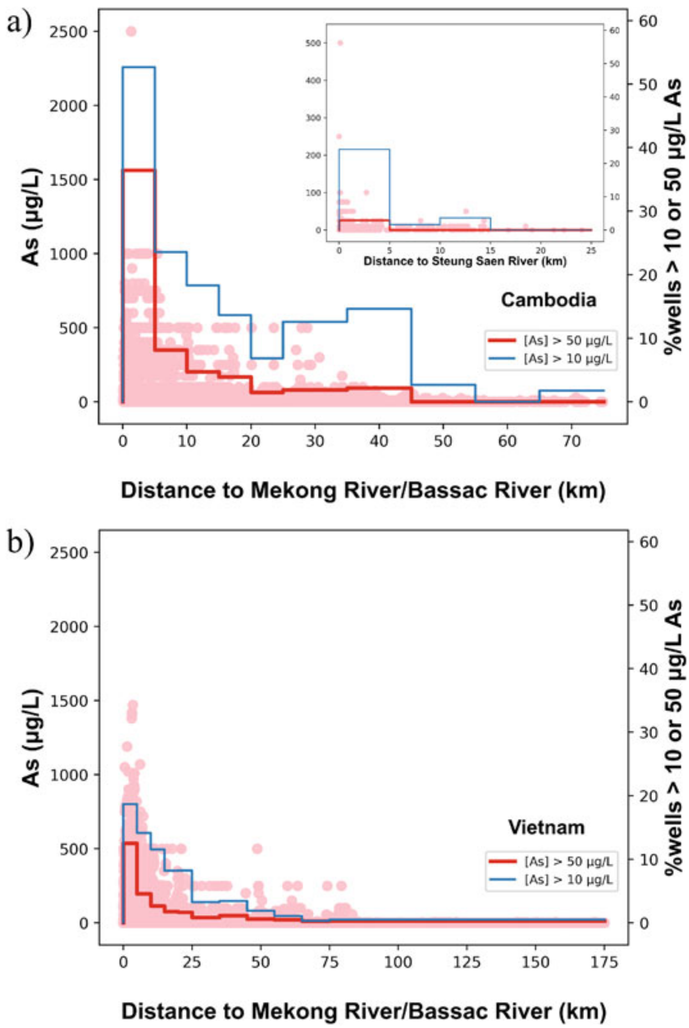


Fig. 4.3 Distribution of well water [As] in 40,305 tested wells with unique values in Cambodia excluding wells located in the northern and westernmost provinces of Cambodia (**a**) and 52,858 tested wells in southern Vietnam (**b**) versus distance to the closest major river course, i.e., Mekong or Bassac Rivers (see Fig. 4.1). The blue and red lines depict the percentages of wells in exceedance of the WHO As guideline the Vietnamese National Drinking Water Standard of 10 µg/L and the Cambodian National Drinking Water Standard of 50 µg/L. For the first 25 km, the analysis is done every 5 km. For wells located at >25 km distance from the closest major river, the analysis is done every 10 km. The inset in (**a**) shows the results of the analysis of 1,439 tested wells in the Steung Saen River watershed, a major tributary of Tonlé Sap

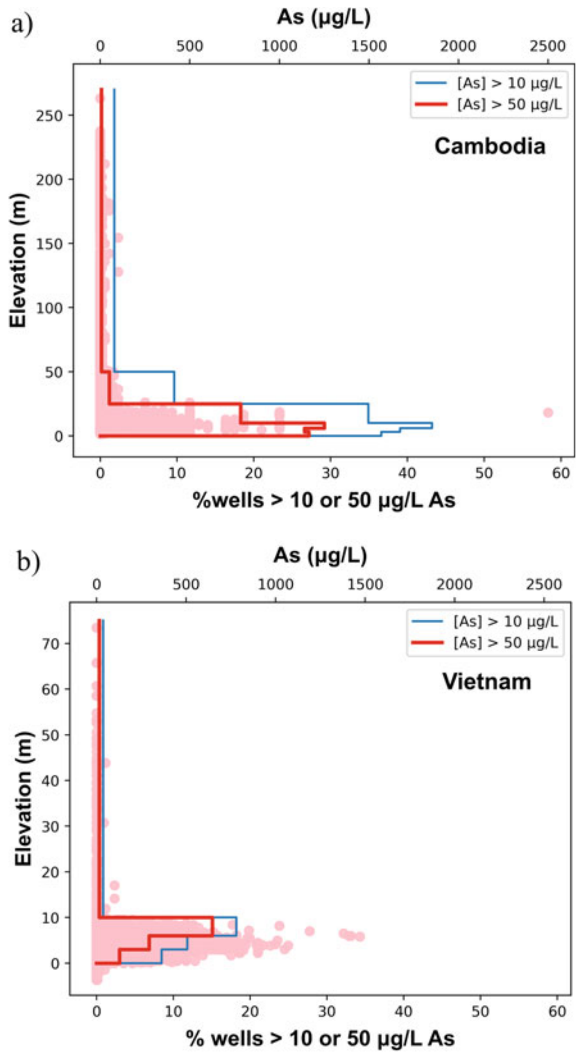


Fig. 4.4 Distribution of well water [As] in Cambodia (**a**) and southern Vietnam (**b**) versus elevation of each well. The red and blue lines describe the percentages of wells that exceed 50 or 10 μg/L As, respectively, and are for the depth ranges of 0–3, 3–6, 6–10, 10–25, 25–50, >50 m for Cambodia (**a**) and 0–3, 3–6, 6–10, >10 m for Vietnam (**b**). The dataset has 41,928 records from Cambodia and 52,858 records from Vietnam

administrative district is well documented by the national census. Each well is "projected" to or "grouped" to its own administrative district based on latitude and longitude. Sub-datasets at the district level with population and a given number of wells with known arsenic concentration are generated. To reduce error, districts with less than 10 wells are not considered in the latter calculation. Using Sohel et al.'s hazard ratios for non-accidental deaths (Sohel et al., 2009), PAF and EDs are estimated for each district in the MRD (Table 4.4). There are 85 administrative districts in 16 provinces in Cambodia with population of 7,750,573 (Table 4.4). The adult (>15 yrs old) population of it was estimated as 5,471,904 by multiplying the total population with the adult age ratio of 70.6% from census. There are 146 administrative districts

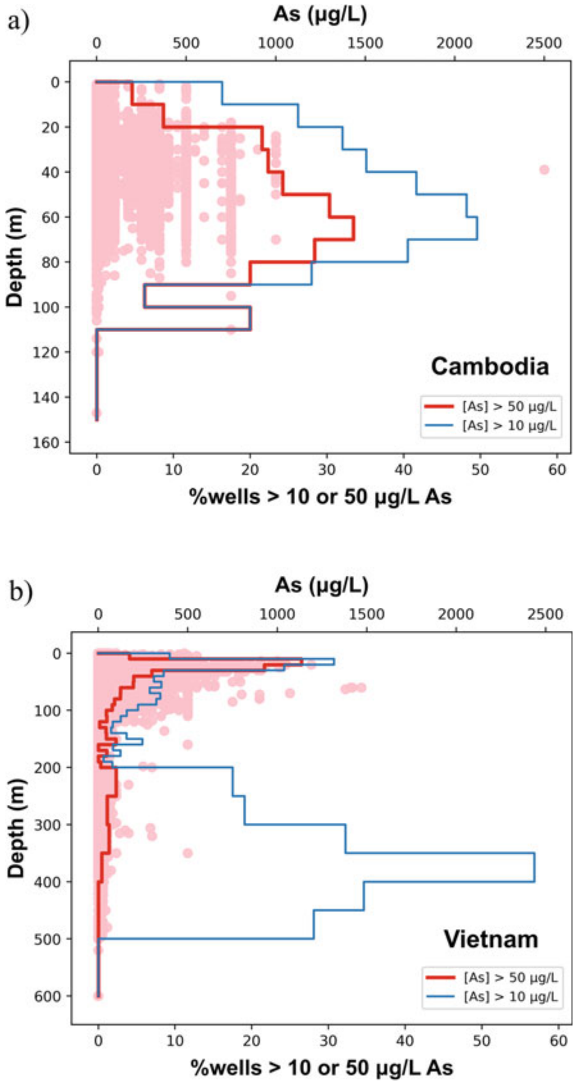


Fig. 4.5 Distribution of well water [As] in Cambodia and southern Vietnam versus depth of each well. The red line describes the percentage of wells that exceed 50 μg/L As while the blue stands for that exceeding 10 μg/L As. For Cambodia, the percentage is calculated every 10 m when the depth is <110 m and for the remainder of the wells with depth >110 m. For Vietnam, the percentage is calculated every 10 m when the depth is <200 m and every 50 m when the depth is >200 m. The dataset has 40,925 records from Cambodia (1003 wells lack the records of well depth) and 52,858 records from Vietnam

for 14 provinces in Vietnam with a population of 24,493,357 (Table 4.4). The adult (>15 yrs old) population of it was estimated as 18,541,471 given the adult age ratio of 75.7% provided by the census.

Table 4.4 Health risks of drinking water As exposure in the Mekong River Delta of Cambodia and Vietnam

Province	District	Population	No. of sample wells by arsenic concentration (in μg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in μg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
Kampong Cham	Batheay	106,997	272	26	2	0	300	0.015	6.2	0.8	0.0	7
	Chamkar Leu	101,675	124	0	0	0	124	0.000	0.0	0.0	0.0	0
	Cheung Prey	92,898	180	3	0	0	183	0.003	1.0	0.0	0.0	1
	Kampong Siem	94,729	500	61	114	118	793	0.094	4.5	13.6	19.5	38
	Kang Meas	85,488	432	236	147	116	931	0.112	13.0	13.2	14.4	41
	Kaoh Soutin	48,069	265	385	345	337	1332	0.170	7.8	11.4	15.4	35
	Krong Kampong Cham	38,365	47	14	6	0	67	0.054	5.1	3.6	0.0	9
	Prey Chhor	133,712	500	4	0	0	504	0.001	0.7	0.0	0.0	1
	Srei Santhor	81,687	288	375	518	180	1361	0.160	12.8	28.8	13.8	55
	Stueng Trang	103,501	90	27	6	1	124	0.048	14.5	5.3	1.2	21
Kampong Chhnang	Baribour	55,371	72	30	10	7	119	0.077	8.7	4.7	4.6	18
	Kampong Leaeng	44,066	17	5	0	0	22	0.035	6.5	0.0	0.0	7
	Kampong Tralach	99,356	146	3	1	0	150	0.005	1.3	0.7	0.0	2
	Krong Kampong Chhnang	41,080	240	51	16	1	308	0.040	4.4	2.3	0.2	7
	Rolea B'ier	103,219	308	21	4	0	333	0.013	4.4	1.3	0.0	6
	Sameakki Mean Chey	81,197	33	1	0	0	34	0.005	1.6	0.0	0.0	2

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Tuek Phos	62,287	96	6	0	0	102	0.009	2.5	0.0	0.0	2
Kampong Speu	Kong Pisei	145,476	27	3	0	0	30	0.016	9.7	0.0	0.0	10
	Odongk	145,311	240	8	0	0	248	0.005	3.2	0.0	0.0	3
	Phnum Sruoch	104,438	20	0	0	0	20	0.000	0.0	0.0	0.0	0
	Samraong Tong	182,774	143	1	1	0	145	0.003	0.9	1.4	0.0	2
Kampong Thom	Baray	104,032	99	8	1	0	108	0.014	5.1	1.0	0.0	6
	Kampong Svay	90,271	177	15	1	1	194	0.015	4.7	0.5	0.7	6
	Krong Stueng Saen	53,118	615	111	22	1	749	0.031	5.2	1.7	0.1	7
	Prasat Ballangk	47,888	65	9	0	0	74	0.019	3.9	0.0	0.0	4
	Prasat Sambour	43,390	151	10	2	0	163	0.013	1.8	0.6	0.0	2
	Sandan	62,013	174	147	12	0	333	0.074	17.2	2.3	0.0	19
	Santuk	101,428	37	5	0	0	42	0.019	8.0	0.0	0.0	8
	Stoung	108,372	273	17	0	0	290	0.009	4.3	0.0	0.0	4
Kandal	Angk Snuol	110,378	505	48	9	5	567	0.020	6.2	1.9	1.5	10
	Kandal Stueng	332,843	1215	292	68	21	1596	0.043	39.5	14.9	6.4	61

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in μg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in μg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Kaoh Thum	129,045	1089	296	661	1310	3356	0.171	6.4	23.2	63.7	93
	Khsach Kandal	140,878	770	253	264	120	1407	0.098	15.5	26.3	16.5	58
	Kien Svay	116,139	430	190	146	605	1371	0.173	9.0	11.3	64.7	85
	Krong Ta Khmau	75,629	1466	273	99	11	1849	0.038	7.3	4.3	0.7	12
	Leuk Daek	54,402	1032	211	223	312	1778	0.103	3.9	6.7	13.1	24
	Lvea Aem	72,211	519	195	144	172	1030	0.112	8.2	9.9	16.3	34
	Mukn Kampul	72,213	140	87	93	89	409	0.146	8.9	15.4	20.5	45
	Popnhea Lueu	103,809	151	33	15	4	203	0.050	10.9	8.0	3.0	22
	S'ang	205,162	2253	658	496	774	4181	0.109	19.5	23.9	51.6	95
Kratie	Chhloung	54,033	300	36	20	4	360	0.033	3.5	3.2	0.9	8
	Krong Kracheh	28,317	207	16	43	7	273	0.056	1.1	4.6	1.0	7
	Preaek Prasab	64,466	83	27	6	10	126	0.070	8.7	3.1	7.3	19
	Sambour	68,730	77	1	0	0	78	0.002	0.6	0.0	0.0	1
	Snuol	92,277	109	3	0	0	112	0.004	1.7	0.0	0.0	2
Otdar Meanchey	Anlong Veaeng	56,927	31	0	0	0	31	0.000	0.0	0.0	0.0	0
Pailin	Krong Pailin	37,393	216	5	0	0	221	0.004	0.6	0.0	0.0	1

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Sala Krau	34,815	130	10	3	0	143	0.016	1.6	0.8	0.0	2
Phnom Penh	Dangkao	159,772	348	91	12	9	460	0.043	20.5	4.4	4.6	29
	Ruessei Kaev	274,861	48	7	2	1	58	0.033	21.7	10.1	7.0	39
Prey Veng	Ba Phnum	80,940	430	51	1	0	482	0.017	5.7	0.2	0.0	6
	Kamchay Mear	84,368	278	21	1	0	300	0.012	4.0	0.3	0.0	4
	Kampong Trabaek	115,119	836	262	43	2	1143	0.045	17.1	4.6	0.3	22
	Kanhchriech	63,012	208	7	0	0	215	0.005	1.4	0.0	0.0	1
	Krong Prey Veaeng	36,254	365	2	2	1	370	0.003	0.1	0.2	0.1	0
	Me Sang	98,531	208	8	0	0	216	0.006	2.5	0.0	0.0	2
	Pea Reang	116,315	732	143	74	111	1060	0.072	9.9	8.3	17.2	35
	Peam Chor	61,454	1120	335	273	464	2192	0.117	5.6	7.4	17.5	31
	Peam Ro	61,456	1616	129	45	51	1841	0.027	2.8	1.6	2.5	7
	Pou Rieng	46,193	584	151	65	31	831	0.059	5.4	3.7	2.5	12
	Preah Sdach	121,113	908	60	2	1	971	0.011	5.0	0.3	0.2	5
	Sithor Kandal	64,167	738	118	1	1	858	0.022	5.8	0.1	0.1	6

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
Pursat	Bakan	103,617	18	1	0	0	19	0.008	3.7	0.0	0.0	4
	Kandieng	54,170	15	0	0	0	15	0.000	0.0	0.0	0.0	0
	Krakor	88,714	31	0	1	0	32	0.008	0.0	3.0	0.0	3
	Phnum Kravanh	50,763	23	0	0	0	23	0.000	0.0	0.0	0.0	0
Siemreap	Angkor Chum	55,176	77	0	0	0	77	0.000	0.0	0.0	0.0	0
	Kralanh	52,447	156	0	0	0	156	0.000	0.0	0.0	0.0	0
	Puok	128,214	157	1	0	0	158	0.001	0.5	0.0	0.0	1
Stung Treng	Krong Stueng Traeng	37,103	15	0	0	0	15	0.000	0.0	0.0	0.0	0
	Sesan	24,630	48	0	0	0	48	0.000	0.0	0.0	0.0	0
	Siem Bouk	23,706	31	0	0	0	31	0.000	0.0	0.0	0.0	0
	Siem Pang	25,390	56	0	0	0	56	0.000	0.0	0.0	0.0	0
	Thala Barivat	36,925	62	0	0	0	62	0.000	0.0	0.0	0.0	0
Svay Rieng	Chantrea	30,481	23	1	0	0	24	0.007	0.9	0.0	0.0	1
	Romeas Haek	108,770	22	0	0	0	22	0.000	0.0	0.0	0.0	0
	Svay Chrum	121,481	59	3	0	0	62	0.008	4.0	0.0	0.0	4

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
Takeo	Bati	158,400	24	0	0	0	24	0.000	0.0	0.0	0.0	0
	Samraong	126,475	75	4	0	0	79	0.008	4.3	0.0	0.0	4
Tboung Khmum	Dambae	87,539	96	1	2	0	99	0.007	0.6	1.9	0.0	3
	Krouch Chhmar	85,187	232	250	53	31	566	0.103	22.9	7.9	6.4	37
	Memot	152,082	156	0	0	0	156	0.000	0.0	0.0	0.0	0
	Ou Reang Ov	79,761	267	10	1	0	278	0.007	1.9	0.3	0.0	2
	Ponhea Kraek	147,310	198	6	0	0	204	0.005	2.9	0.0	0.0	3
	Tboung Khmum	176,802	272	109	20	5	406	0.057	30.3	9.0	3.1	43
Vietnam		**24,493,357**	**47,583**	**2706**	**1062**	**1506**	**52,857**	**0.013**	**709**	**294**	**483**	**1486**
An Giang	An Phu	148,615	69	18	168	427	682	0.227	2.3	35.1	123.5	161
	Chau Doc	101,765	38	0	0	0	38	0	0	0	0	0
	Chau Phu	206,676	129	2	6	2	139	0.018	2.2	10.6	4.9	18
	Chau Thanh	151,368	273	1	0	2	276	0.003	0.4	0	1.8	2
	Cho Moi	307,981	683	41	36	31	791	0.033	11.7	16.8	20	48
	Long Xuyen	272,365	394	40	10	3	447	0.022	18.1	7.4	3.1	29
	Phu Tan	188,951	228	7	49	74	358	0.102	2.5	28.9	60.5	92

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Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Tan Chau	141,211	405	34	55	69	563	0.073	6	15.8	27.4	49
	Thoai Son	163,427	230	71	0	0	301	0.036	28.1	0	0	28
	Tinh Bien	108,562	194	0	0	0	194	0	0	0	0	0
	Tri Ton	117,431	483	2	1	0	486	0.001	0.3	0.3	0	1
Bac Lieu	Bac Lieu	156,110	197	0	0	0	197	0	0	0	0	0
	Dong Hai	152,619	168	0	0	0	168	0	0	0	0	0
	Gia Rai	143,613	168	0	0	0	168	0	0	0	0	0
	Hoa Binh	117,753	191	0	0	0	191	0	0	0	0	0
	Hong Dan	111,848	158	0	0	0	158	0	0	0	0	0
	Phuoc Long	124,268	168	0	0	0	168	0	0	0	0	0
	Vinh Loi	101,025	193	0	0	0	193	0	0	0	0	0
Ben Tre	Ba Tri	184,734	1580	104	31	21	1736	0.018	8.2	4	3.7	16
	Binh Dai	137,304	724	71	28	40	863	0.037	8.3	5.3	10.6	24
	Chau Thanh	175,893	244	2	4	1	251	0.007	1.1	3.6	1.2	6
	Cho Lach	111,418	20	2	0	0	22	0.014	7.4	0	0	7
	Giong Trom	169,987	655	51	12	2	720	0.016	8.8	3.4	0.8	13

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Mo Cay Bac	113,210	143	4	4	0	151	0.011	2.3	3.7	0	6
	Mo Cay Nam	143,577	448	15	15	37	515	0.037	3.1	5	17.2	25
	Thanh Phu	127,841	809	61	43	62	975	0.042	5.8	6.6	13.2	26
Ca Mau	Ca Mau	226,372	167	0	0	0	167	0	0	0	0	0
	Cai Nuoc	136,638	168	0	0	0	168	0	0	0	0	0
	Dam Doi	175,629	168	0	0	0	168	0	0	0	0	0
	Nam Can	56,813	121	0	0	0	121	0	0	0	0	0
	Ngoc Hien	66,874	81	0	0	0	81	0	0	0	0	0
	Phu Tan	97,703	96	0	0	0	96	0	0	0	0	0
	Thoi Binh	135,892	98	0	0	0	98	0	0	0	0	0
	Tran Van Thoi	197,679	190	0	0	0	190	0	0	0	0	0
	U Minh	100,876	96	0	0	0	96	0	0	0	0	0
Can Tho	Binh Thuy	142,164	435	47	11	1	494	0.021	10	3.8	0.5	14
	Cai Rang	105,393	127	15	1	0	143	0.018	8.2	0.9	0	9
	Co Do	116,576	70	3	0	0	73	0.007	3.9	0	0	4
	Ninh Kieu	280,494	83	2	0	0	85	0.004	5.4	0	0	5

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Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	O Mon	128,677	476	31	3	0	510	0.011	5.8	0.9	0	7
	Phong Dien	98,424	365	20	1	0	386	0.009	3.9	0.3	0	4
	Thoi Lai	109,684	86	3	0	0	89	0.005	2.6	0	0	3
	Thot Not	155,360	468	15	9	1	493	0.01	3.5	3.4	0.5	7
	Vinh Thanh	98,399	656	23	2	2	683	0.007	2.5	0.3	0.5	3
Dong Thap	Cao Lanh	164,835	923	22	15	46	1006	0.023	2.7	2.9	12.5	18
	Cao Lanh	197,614	292	0	0	0	292	0	0	0	0	0
	Chau Thanh	146,812	115	2	0	1	118	0.006	2	0	2.2	4
	Hong Ngu	76,462	459	52	52	87	650	0.076	4.3	7	16.3	28
	Hong Ngu	120,571	112	0	0	0	112	0	0	0	0	0
	Lai Vung	164,240	412	1	0	2	415	0.002	0.3	0	1.3	2
	Lap Vo	180,627	218	16	3	1	238	0.015	8.9	2.7	1.3	13
	Sa Dec	106,198	358	3	5	2	368	0.007	0.7	1.8	1	4
	Tam Nong	99,995	153	0	0	0	153	0	0	0	0	0
	Tan Hong	75,456	1036	88	42	18	1184	0.026	4.2	3.2	1.9	9
	Thanh Binh	134,903	145	28	131	442	746	0.209	3	23.2	108.2	134

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Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Thap Muoi	131,791	480	2	0	0	482	0.001	0.6	0	0	1
Hau Giang	Chau Thanh	97,606	556	39	9	0	604	0.014	4.7	1.8	0	7
	Chau Thanh	88,079	112	2	0	0	114	0.003	1.3	0	0	1
	Long My	77,346	235	5	1	0	241	0.004	1.1	0.4	0	1
	Long My	62,339	89	0	0	0	89	0	0	0	0	0
	Nga Bay	56,182	91	0	0	0	91	0	0	0	0	0
	Phung Hiep	188,017	299	20	6	2	327	0.016	8.4	4.1	1.9	14
	Vi Thanh	73,322	118	2	0	0	120	0.003	1	0	0	1
	Vi Thuy	90,126	273	10	5	2	290	0.012	2.3	1.9	1	5
Ho Chi Minh	Binh Chanh	705,508	265	0	0	0	265	0	0	0	0	0
	Can Gio	71,526	17	0	0	0	17	0	0	0	0	0
	Cu Chi	462,047	326	1	0	1	328	0.002	1.4	0	3.1	4
	Hoc Mon	542,243	207	0	0	0	207	0	0	0	0	0
	Nha Be	206,837	67	4	0	0	71	0.009	8.9	0	0	9
	Quarter 10	234,819	77	0	0	0	77	0	0	0	0	0
	Quarter 11	209,867	49	0	0	0	49	0	0	0	0	0

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Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Quarter 12	620,146	303	0	0	0	303	0	0	0	0	0
	Quarter 2	180,275	147	0	0	0	147	0	0	0	0	0
	Quarter 6	233,561	38	0	0	0	38	0	0	0	0	0
	Quarter 8	424,667	47	0	0	0	47	0	0	0	0	0
	Quarter 9	397,006	233	0	0	0	233	0	0	0	0	0
	Quarter Binh Tan	784,173	279	1	0	0	280	0.001	3.7	0	0	4
	Quarter Binh Thanh	499,164	97	0	0	0	97	0	0	0	0	0
	Quarter Go Vap	676,899	219	0	0	0	219	0	0	0	0	0
	Quarter Tan Binh	474,792	120	0	0	0	120	0	0	0	0	0
	Quarter Tan Phu	485,348	384	0	0	0	384	0	0	0	0	0
	Quarter Thu Duc	592,686	137	5	1	0	143	0.007	14.9	4.9	0	20
Kien Giang	An Bien	115,218	601	6	3	0	610	0.003	0.9	0.7	0	2
	An Minh	115,720	200	0	0	0	200	0	0	0	0	0
	Chau Thanh	159,607	277	0	0	0	277	0	0	0	0	0
	Giang Thanh	29,215	118	0	0	0	118	0	0	0	0	0

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Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in μg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in μg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Giong Rieng	224,655	174	0	0	0	174	0	0	0	0	0
	Go Quao	132,508	349	0	2	0	351	0.001	0	0.6	0	1
	Ha Tien	48,495	324	1	6	1	332	0.006	0.1	1	0.2	1
	Hon Dat	156,273	320	0	0	0	320	0	0	0	0	0
	Kien Luong	79,484	140	0	0	0	140	0	0	0	0	0
	Rach Gia	227,527	1380	22	13	0	1415	0.005	2.8	2.7	0	5
	Tan Hiep	125,459	594	21	6	0	621	0.008	3.3	1.5	0	5
	U Minh Thuong	63,415	160	0	0	0	160	0	0	0	0	0
	Vinh Thuan	81,875	199	0	0	0	199	0	0	0	0	0
Long An	Ben Luc	181,660	420	0	0	0	420	0	0	0	0	0
	Can Duoc	187,359	546	0	0	0	546	0	0	0	0	0
	Can Giuoc	214,914	993	2	1	1	997	0.001	0.3	0.3	0.4	1
	Chau Thanh	109,812	353	41	14	0	408	0.024	8.1	4.5	0	13
	Duc Hoa	315,711	1302	15	3	0	1320	0.002	2.3	0.7	0	3
	Duc Hue	65,961	384	0	0	0	384	0	0	0	0	0
	Kien Tuong	43,674	209	2	0	0	211	0.002	0.4	0	0	0

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Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in μg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in μg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Moc Hoa	28,165	224	1	2	1	228	0.005	0.1	0.3	0.2	1
	Tan An	145,120	588	125	14	1	728	0.032	18.5	3.4	0.3	22
	Tan Hung	47,651	704	3	2	0	709	0.001	0.1	0.1	0	0
	Tan Thanh	77,537	346	1	0	0	347	0	0	0	0	0
	Tan Tru	66,502	149	0	0	0	149	0	0	0	0	0
	Thanh Hoa	56,074	198	0	0	0	198	0	0	0	0	0
	Thu Thua	98,333	177	1	0	0	178	0.001	0.5	0	0	0
	Vinh Hung	50,074	376	4	8	0	388	0.007	0.4	1.3	0	2
Soc Trang	Chau Thanh	95,188	483	57	14	1	555	0.023	7.3	2.9	0.3	10
	Cu Lao Dung	58,304	119	1	0	0	120	0.001	0.3	0	0	0
	Ke Sach	149,156	332	9	3	0	344	0.006	2.8	1.5	0	4
	Long Phu	94,255	290	3	1	0	294	0.003	0.9	0.5	0	1
	My Tu	90,524	546	66	35	5	652	0.032	6.8	5.9	1.2	14
	My Xuyen	150,067	275	12	2	0	289	0.008	4.5	1.2	0	6
	Nga Nam	74,115	258	3	7	4	272	0.014	0.6	2.4	1.9	5
	Soc Trang	137,305	272	5	0	0	277	0.003	2	0	0	2

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in µg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in µg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Thanh Trj	73,596	314	5	4	0	323	0.006	0.9	1.2	0	2
	Tran De	112,463	455	26	8	0	489	0.013	4.6	2.3	0	7
	Vinh Chau	164,680	291	5	0	0	296	0.003	2.4	0	0	2
Tien Giang	Cai Be	292,738	262	196	0	0	458	0.064	89.4	0	0	89
	Cai Lay	193,328	282	68	0	0	350	0.03	27.7	0	0	28
	Cai Lay	125,615	492	53	0	0	545	0.015	9	0	0	9
	Chau Thanh	263,426	904	173	4	1	1082	0.026	31.1	1.2	0.4	33
	Cho Gao	187,711	256	203	11	0	470	0.07	57.6	5.1	0	63
	Go Cong	99,657	49	8	0	0	57	0.022	10.5	0	0	10
	Go Cong Tay	127,132	73	85	3	0	161	0.082	47	2.7	0	50
	My Tho	228,109	355	99	5	1	460	0.037	36.4	3	0.8	40
	Tan Phuoc	65,331	247	74	4	0	325	0.038	10.9	1	0	12
Tra Vinh	Cang Long	147,694	254	10	1	0	265	0.007	4.2	0.7	0	5
	Cau Ke	102,767	143	0	0	0	143	0	0	0	0	0
	Cau Ngang	121,254	318	16	2	0	336	0.009	4.3	0.9	0	5
	Chau Thanh	144,040	201	1	0	0	202	0.001	0.7	0	0	1

(continued)

Table 4.4 (continued)

Province	District	Population	No. of sample wells by arsenic concentration (in μg/L) and in total					PAF[a]	No. of excess deaths by arsenic concentration (in μg/L) and in total			Excess death
			0–10	10–50	50–150	≥150	Total		10–50	50–150	≥150	
Cambodia		7,750,573	26,886	5987	4096	4914	41,883	0.037	492	314	398	1204
	Duyen Hai	78,444	268	7	3	0	278	0.007	1.5	1.1	0	3
	Duyen Hai	48,210	201	3	3	0	207	0.006	0.5	0.9	0	1
	Tieu Can	107,846	141	1	0	0	142	0.001	0.5	0	0	1
	Tra Cu	146,329	345	6	1	0	352	0.003	1.6	0.4	0	2
Vinh Long	Binh Minh	94,862	1394	94	38	36	1562	0.024	4.3	2.8	3.7	11
	Binh Tan	95,709	875	59	25	34	993	0.028	4.3	2.9	5.6	13
	Long Ho	167,698	25	3	1	0	29	0.025	13	7	0	20
	Mang Thit	96,172	24	0	0	0	24	0	0	0	0	0
	Tam Binh	151,520	1189	70	37	25	1321	0.022	6	5.1	4.8	16
	Tra On	129,589	1194	23	6	1	1224	0.005	2	0.9	0.2	3
	Vinh Long	137,870	15	7	1	1	24	0.068	28.8	6.7	9.3	45
	Vung Liem	149,371	205	22	10	14	251	0.043	9.7	7.1	13.8	31

[a] Districts with population attributable fraction (PAF) > 0.1 are marked red

4.2.3 Spatial Characteristics of Well Water Arsenic Exposure and Health Effects

Extremely High As Occurrence Within 5 km Distance of the Mekong-Bassac Rivers. Groundwater As concentration data (n = 94,786) in the MRD region of Cambodia and Southern Vietnam exhibits a clear spatial pattern with high As wells located in proximity to the main course of the Mekong and Bassac Rivers (Fig. 4.2a). It is also evident that Cambodia is hit harder by As than Vietnam. In Cambodia, 35.8% of 41,928 wells tested contain >10 μg/L As, while in Vietnam this percentage is only 10.0% among 52,859 wells (Table 4.2). Moreover, 11.7% of the Cambodian wells displayed >150 μg/L As, far greater than the 2.8% in Vietnam.

Our distance analysis unequivocally demonstrates that in most of the high [As] wells, regardless of whether the definition of high level is relative to 10 or 50 μg/L, the percentages of such high [As] wells is the highest within 5 km distance of the closest major river (mostly Mekong and Bassac), and decreases quickly within 20 km of distance (Fig. 4.3). This decreasing trend continues for wells located 20 km and further distance away from the closest major river, albeit more gradually (Fig. 4.3). In Cambodia, 36.2% of the wells located within 5 km of the Mekong River contain >50 μg/L of As; but this percentage drops significantly to <10% from 5 km onwards (Fig. 4.3a). Although the decline is less dramatic, 52.3% of the wells located within 5 km of the Mekong River contain >10 μg/L of As, decreasing to less than 20% when the distance is >25 km (Fig. 4.3a). In Vietnam, 12.5 and 18.7% of the wells within 5 km of the Mekong River are affected by As greater than 50 and 10 μg/L, respectively. The percentage of wells exceeding 50 and 10 μg/L lowers to less than 5 and 15% when the wells are located between 5 and 25 km distance. Beyond 25 km, the percentage of wells with As concentration >50 and >10 μg/L are less than 1 and 2% respectively (Table 4.3).

In Cambodia, 78.6 and 90.5% of wells with As concentrations greater than 10 and 50 μg/L respectively are within the first 5 km of the Mekong/Bassac River. Kaoh Soutin, a district in the province of Kampong Cham, shows the highest exceedance rate, with 80.1% of 1,335 tested wells containing >10 μg/L As, with an average As concentration of 107 μg/L. It is also where the country's highest As (2500 μg/L) well (distance to Mekong 1.3 km, elevation 18 m, depth 39 m) is located. Furthermore, a total of 16 wells in Kaoh Soutin displayed 1000 μg/L of As, or the second highest level in the field test kit used. Using 50 μg/L of As as a benchmark, Kaoh Thum, a district in the province of Kandal, has the largest percentage of wells not meeting the Cambodian drinking water standard (58.7%). Both Kaoh Soutin and Kaoh Thum are located adjacent to the Mekong with PAF > 0.1 (Table 4.4). For the wells located in the Steung Saen River watershed, a similar descending trend of As concentration and exceedance rates is evident (Fig. 4.3a inset). Here, 3.0 and 24.2% of wells within the first 5 km of this smaller river contained >50 and >10 μg/L As, with the maximum, mean and median As concentration of 500, 13.7 and 10.0 μg/L, respectively. The well with the highest As concentration is found 100 m from the Steung Saen, with a depth of 26 m and an elevation of 12.8 m.

In Vietnam, 52.8 and 72.6% of wells containing greater than 10 or 50 μg/L are within the first 5 km of the main courses of the Mekong-Bassac Rivers. The highest As point of 1,470 μg/L is found in Cao Lanh, a district of Dong Thap province. Its well depth is 60 m and it is located 3.3 km away from the Mekong River with an elevation of 5.8 m. The district with the highest exceedance rate relative to 10 and 50 μg/L is An Phu from An Giang Province, with the percentages being 89.9 and 87.2% respectively. An Phu is adjacent to the Mekong River, with an extraordinary PAF of 0.22 (Table 4.4).

High Arsenic Occurrence in Low-Lying Areas with <25 m Elevation in Cambodia and <10 m Elevation in Vietnam

In Cambodia, the vast majority of the high arsenic wells (98.3% of all >10 μg/L wells and 99.7% of all >50 μg/L wells) are located below an elevation of 25 m (Fig. 4.4a). In this low-lying area, 38.5% of tested wells had >10 μg/L of As and 23.4% of tested wells had >50 μg/L of As. The maximum, median and mean arsenic concentration among wells at elevations below 25 m is 2500, 10.0 and 63.9 μg/L, respectively. The corresponding values are 500, 0 and 3.6 μg/L when the elevation is higher than 25 m. The highest occurrence rate of groundwater arsenic is from wells located at elevations between 6 and 10 m above sea level, with 29.2 and 43.2% of wells containing greater than 10 or 50 μg/L As, respectively.

In Vietnam, most of the high arsenic wells (99.9% of all >10 μg/L wells and 99.9% of all >50 μg/L wells), are located below an elevation of 10 m in the MRD of Vietnam (Fig. 4.4b). In this low-lying area, 10.1% of tested wells had >10 μg/L of As and 4.9% of tested wells had >50 μg/L of As. The maximum, median and mean arsenic concentration among wells at elevations below 10 m is 1470, 0 and 14.6 μg/L, respectively (Table 4.3). The corresponding values are 100, 0 and 1.0 μg/L when the elevation is higher than 10 m (Table 4.3). The highest occurrence rate of groundwater arsenic is from wells located at elevations between 6 and 10 m above sea level, with 18.2 and 15.1% of wells containing greater than 10 or 50 μg/L As, respectively.

High Arsenic Occurrence at Shallow Depths (<70 m) Across the MRD and at Deep Depths (300–500 m) in Vietnam

In Cambodia, the majority of the wells (99.3%) are from the shallow aquifer with a depth of <70 m (Fig. 4.5a) and a mean depth of 35.2 m. It is noted that only 40,925 wells from 41,928 wells have depth records. Wells with depths between 60 and 70 m exhibit the largest proportion of high concentrations of As, with 49.6% > 10 μg/L and 33.4% > 50 μg/L. The maximum, median and mean values are 1000, 10.0 and 125.2 μg/L for depth intervals in this range. At depth >80 m, the percentage of high As wells, relative to both 10 and 50 μg/L, decrease to <17 and <14%, respectively.

In Vietnam, there are two distinct As peaks at shallow (~30 m) and deep (~350 m) depths (Fig. 4.5b). Still, the majority of the high arsenic wells (78.6% of all >10 μg/L wells and 95.4% of all >50 μg/L wells) are from the shallow aquifer with a depth <100 m (Fig. 4.5b). Wells with depths between 10 and 20 m exhibit the largest proportion of having a high concentration of As > 50 μg/L, with 30.7% > 10 μg/L and

26.5% > 50 μg/L. For wells with depths between 200 and 500 m, the exceedance rate diverges depending on whether 10 or 50 μg/L is used as a benchmark for comparison. Less than 1.5% of wells in this depth interval contain >50 μg/L but a staggering 26.1% of wells contain >10 μg/L of As (Fig. 4.5b), reaching a peak occurrence of 56.8% for wells with depth between 350 and 400 m. The maximum, median and mean values of wells between 350 and 400 m are 70, 20.0 and 15.5 μg/L, respectively.

Extreme Human Health Tolls Identified in 14 Districts of Cambodia and Vietnam

A total of 14 districts, 11 in Cambodia and 3 in Vietnam, are at very high risk (defined as when the PAF value is >0.1) from exposure to arsenic in drinking water, which means 10% of the total deaths are attributable to arsenic alone (Table 4.4 and Fig. 4.1). The average PAF values of all districts evaluated here in Cambodia and Vietnam are 0.037 and 0.013 respectively. However, due to the distinct spatial distribution pattern with high percentage As wells located within 20 km and especially within 5 km of the main courses of the Mekong and Bassac Rivers, districts adjacent to the Mekong show extreme PAF values greater than 0.15, and they are Kaoh Soutin, Kien Svay, Kaoh Thum and Srei Santhor in Cambodia (n = 4) and An Phu and Thanh Binh in Vietnam (n = 2, Table 4.4). Since the PAF represents the percentage of total deaths that are "preventable" or can be eliminated under the normal condition without arsenic exposure, this is a serious health crisis for these 14 districts in the MRD where about 1.5 million people reside: more than one in every ten people die due to exposure to drinking water As alone. In these 14 districts of the MRD, the annual excess death from high arsenic in water is 575 in 11 districts of Cambodia and 387 in 3 districts of Vietnam, representing about 17.2% (or 1 in every 6 adult deaths) and 13.4% (or 1 in every 8 adult deaths) of the total adult deaths in the most severely affected districts along the Mekong-Bassac Rivers. The annual excess death from high arsenic is 1204 in Cambodia and 1486 in Vietnam, representing about 3.66% (or 1 in every 27 adult deaths) and 1.27% (or 1 in every 78 adult deaths) of the total deaths in the entire MRD regions of two countries assessed here.

Although the average PAF (0.037) of Cambodia is higher than that (0.013) of Vietnam, the number of excess deaths estimated in Vietnam is actually more because the population is higher. Overall, Vietnam has a higher population density than Cambodia (Fig. 4.2b), with 70.7% of the districts having more than 10,000 people while in Cambodia the percentage is only 38.8%, which makes the distribution of excess death in Fig. 4.2d different from the PAF distribution (Fig. 4.2c).

4.2.4 Strength and Weakness of the Water As Health Effect Assessment

A strength of our health assessment is the large sample size from various sources. The districts of Cambodia and southern Vietnam have on average, 453 and 400 groundwater arsenic records respectively, making the estimation have a better chance of capturing the spatially heterogenous As distribution pattern. Although a health effect assessment of individual disease outcomes, such as various internal cancers, is desirable, using PAF to assess ED is robust. Without a death registry that carefully classifies the cause of death, it remains difficult to make the linkage between As exposure and death to verify detailed disease outcomes predicted based on dose–response established elsewhere (Hong et al., 2014).

One potential source of bias in our analysis is the use of the proportion of wells exceeding the drinking water quality standard as a proxy for individual exposure. In Cambodia, water resources are unevenly distributed in time and space. People are faced with water shortages in most of the rural areas during the dry season while there is plenty of water that floods wetlands, lowland areas and human habitats in the rainy season. This implies that people may not use well water consistently over time. Another bias comes from the number of people relying on wells for their daily drinking water. According to the National Institute of Statistics of the Ministry of Planning, only 23.7% of the total population in Cambodia had access to safe drinking water, with 30.4% of people using surface water or dug wells. In 2020, the percentage of people drinking surface water has decreased to 9.2%, with 53.2% of people drinking non-piped water from tube/dug wells etc.

Unfortunately, drinking water sources in the lower MRD do not exist to provide a clear linkage to As. Table 4.5 shows the proportions of household drinking water sources in 16 provinces of Cambodia and 14 provinces of Vietnam based on the national census reports of the respective country in 2019. Assuming that groundwater likely contains arsenic but surface water likely does not, tube wells, boreholes, and protected or unprotected wells are classified as drinking water sources at risk. Water sources with negligible risk of arsenic include rainwater collection and surface water (river, stream, dam, lake). Piped into dwellings, tanker trucks, public taps, etc., are considered uncertain because they can be sourced from either groundwater or surface water. Overall, 47.1% of rural families in Cambodia still drink well water, inferring a severe health hazard. In Vietnam, the categories of source water are slightly different so are similarly "assigned" a likelihood of As risk. It is worth noting that 56.9% of Vietnamese households have access to tap water. However, a survey of water consumption patterns in Can Tho City and An Giang Province found that only <20% of households used piped water for drinking (Chau et al., 2015). There may also be a rural and urban disparity. A survey of 542 rural households from Can Tho, Hau Giang, and Soc Trang provinces in Vietnam has found that 27% of the survey respondents with access to a piped-water supply did not use it, and 30% of them used this water for washing and cleaning (Wilbers et al., 2014). More importantly, of 41 piped-water supply stations investigated, 24 stations are sourced from groundwater while 17 used surface water. With this uncertainty in mind, Table 4.5 includes a "possible risk" category which includes all types of wells and piped-water supply. Although one might argue that only about half of the population is at risk of drinking high arsenic from groundwater, the spatial patterns of health burden remain robust although the excess deaths for each district should be adjusted downward if the population relying on well water is known.

Table 4.5 Household drinking water sources in 16 provinces of Cambodia and 14 provinces of Vietnam according to 2019 national census

Province (Cambodia)	Source of drinking water (%)							
	Possible risk		Risk of elevated arsenic				Uncertain	
	Well and piped into dwelling etc.	Total	Tube well, borehole	Protected well	Unprotected well	Total	Public tap/standpipe	Tanker truck
Total	64.7	35.6	25.2	4.5	5.9	51.0	3.9	4.9
Urban	68.1	16.5	12.9	2.2	1.4	76.8	5.7	4.8
Rural	62.8	47.1	32.6	5.9	8.6	35.8	2.8	5.0
Kampong Cham	75.5	42.5	27.7	8.1	6.7	50.6	6.6	2.3
Kampong Chhnang	71.4	56.1	36.5	6.4	13.2	34.7	3.3	2.0
Kampong Speu	44.8	20.6	15.3	3.4	1.9	65.2	8.1	17.8
Kampong Thom	73.5	61.2	22.1	14.2	24.9	29.2	2.6	1.4
Kandal	73.3	14.9	12.6	1.8	0.5	75.3	6.5	3.9
Kratie	51.3	25.2	12.6	5.2	7.4	61.5	2.1	11.1
Otdar Meanchey	29.9	21.2	14.0	3.6	3.6	52.8	1.0	21.3
Pailin	28.0	5.0	3.7	0.4	0.9	68.7	1.8	11.0
Phnom Penh	78.0	2.8	2.4	0.3	0.1	94.6	4.3	2.6
Prey Veng	87.5	70.9	70.0	0.6	0.3	25.2	1.5	0.1
Pursat	49.7	33.8	16.8	5.8	11.2	34.3	3.4	7.6
Siem Reap	70.9	56.3	39.1	8.3	8.9	35.5	2.5	3.9
Stung Treng	38.1	26.0	14.5	5.2	6.3	27.8	1.5	7.8
Svay Rieng	94.6	84.5	83.9	0.3	0.3	14.7	1.9	0.0
Takeo	52.4	31.6	23.3	3.9	4.4	45.5	4.4	3.4
Tboung Khmum	89.2	72.1	51.2	10.8	10.1	27.2	3.2	0.5

(continued)

Table 4.5 (continued)

Province (Cambodia)	Source of drinking water (%)							
	Uncertain						Negligible risk of elevated arsenic	
	Piped into dwelling, compound, yard or plot	Protected/ unprotected spring	Cart with small tank/ drum	Bottled water	Other	Total	Rainwater collection	Surface water (river, stream, dam, lake)
Total	29.1	0.6	4.8	7.1	0.6	13.4	2.8	10.6
Urban	51.6	0.3	4.0	9.8	0.6	6.9	1.5	5.4
Rural	15.7	0.9	5.3	5.4	0.7	17.2	3.5	13.7
Kampong Cham	33.0	0.5	4.1	3.5	0.6	6.8	1.2	5.6
Kampong Chhnang	15.3	0.7	6.8	5.9	0.7	9.1	0.4	8.7
Kampong Speu	24.2	0.3	11.4	2.9	0.5	14.2	2.4	11.8
Kampong Thom	12.3	1.3	5.3	4.8	1.5	9.5	0.7	8.8
Kandal	58.4	0.3	3.0	3.0	0.2	9.8	0.7	9.1
Kratie	26.1	0.4	4.9	16.0	0.9	13.3	0.1	13.2
Otdar Meanchey	8.7	0.5	11.2	9.9	0.2	26.0	1.2	24.8
Pailin	23.0	0.4	1.6	30.3	0.6	26.3	4.8	21.5
Phnom Penh	75.2	0.1	2.0	9.9	0.5	2.6	0.3	2.3
Prey Veng	16.6	0.3	1.7	4.6	0.4	3.8	0.2	3.6
Pursat	15.9	1.1	3.6	2.3	0.4	31.8	3.4	28.4
Siem Reap	14.6	1.1	5.9	6.3	1.2	8.3	0.5	7.8
Stung Treng	12.1	0.4	1.8	4.0	0.2	46.1	0.0	46.1

(continued)

Table 4.5 (continued)

Province (Cambodia)	Source of drinking water (%)							
	Uncertain						Negligible risk of elevated arsenic	
	Piped into dwelling, compound, yard or plot	Protected/ unprotected spring	Cart with small tank/ drum	Bottled water	Other	Total	Rainwater collection	Surface water (river, stream, dam, lake)
Svay Rieng	10.1	0.4	0.8	1.0	0.5	0.9	0.2	0.7
Takeo	20.8	0.9	11.4	4.3	0.3	23.1	7.5	15.6
Tboung Khmum	17.1	0.3	2.1	3.0	1.0	0.7	0.2	0.5

Province (Vietnam)	Source of water for living (%)					
	Possible risk		Risk of elevated arsenic			
	Risk of elevated arsenic and Tap water	Total	Drilled Well	Protected dig well	Unprotected dig well	Total
Mekong River Delta Region	83.2	26.3	25.8	0.4	0.1	64.5
An Giang	92.2	1.3	0.9	0.3	0.1	97.7
Bac Lieu	90.4	48.7	48.0	0.6	0.1	50.5
Ben Tre	49.9	2.2	1.6	0.5	0.1	56.7
Ca Mau	82.1	55.9	55.6	0.3	0.0	36.3
Can Tho	96.0	5.1	5.0	0.1	0.0	94.2
Dong Thap	87.9	3.0	2.6	0.2	0.2	95.5
Hau Giang	86.3	36	35.6	0.3	0.1	56.1
Ho Chi Minh	96.5	5.0	4.8	0.2	0.0	95.0
Kien Giang	74.8	39	37.6	1.2	0.2	40.5
Long An	82.2	43.8	42.7	1.0	0.1	49.8
Soc Trang	89.1	37.6	37.4	0.1	0.1	59.0
Tien Giang	81.2	48.4	48.1	0.3	0.0	39.0

(continued)

Table 4.5 (continued)

Province (Vietnam)	Source of water for living (%)					
	Possible risk		Risk of elevated arsenic			
	Risk of elevated arsenic and Tap water	Total	Drilled Well	Protected dig well	Unprotected dig well	Total
Tra Vinh	87.2	38.0	37.3	0.6	0.1	57.5
Vinh Long	91.4	2.8	2.7	0.0	0.1	94.6

Province (Vietnam)	Source of water for living (%)						
	Uncertain				Negligible risk of elevated arsenic		
	Tap water	Purchased water (xitec, vase)	Others	Total	Protected slot water	Unprotected slot water	Rainwater
Mekong River Delta Region	56.9	5.9	1.7	9.2	0.1	0	9.1
An Giang	90.9	4.1	2.7	1.1	0.0	0.1	1.0
Bac Lieu	41.7	8.7	0.1	0.8	–	–	0.8
Ben Tre	47.7	4.8	4.2	41.2	–	–	41.2
Ca Mau	26.2	10.1	0.0	7.8	–	–	7.8
Can Tho	90.9	3.2	0.1	0.9	–	–	0.9
Dong Thap	84.9	4.6	6.0	1.6	0.0	0.1	1.5
Hau Giang	50.3	3.8	2.0	7.9	0.0	0.0	7.9
Ho Chi Minh	91.5	3.5	0.0	0	–	–	–
Kien Giang	35.8	4.2	0.5	20.5	0.4	0.0	20.1
Long An	38.4	11.2	0.2	6.3	–	–	6.3
Soc Trang	51.5	7.1	0.4	3.5	–	–	3.5
Tien Giang	32.8	6.1	0.1	12.6	0.1	–	12.5
Tra Vinh	49.2	8.1	0.2	4.6	0.0	0.0	4.6
Vinh Long	88.6	1.3	4.7	2.6	–	–	2.6

4.3 Sediment Depositional Environment of the MRD During the Holocene

To set the stage for rice arsenic health risk assessment, this section examines existing literature on the sediment depositional environment of the MRD from the early Holocene to provide the geologic context for the formation of the soil and aquifer. This synthesis is relevant to Sects. 4.4 and 4.5 which describe the arsenic cycling in the MRD soils, the linkage between paddy soil and rice arsenic, as well as the soil and rice contamination risks associated with irrigation using arsenic-enriched groundwater. It also provides the framework to understand the findings emerged from hydrogeochemical studies in the MRD that sought to explain the occurrence of elevated groundwater arsenic in the low-lying areas, summarized briefly as follows.

Buschmann et al. (2007) have investigated mechanisms for geogenic arsenic mobilization triggered by anoxic conditions of the MRD aquifer, observing that elevated groundwater As levels are only present in the flat land embraced by the Mekong and Bassac Rivers. A possible explanation is that this in-between-river area was incised by the rivers during the Pleistocene glaciation, and only filled with alluvial deposits during the Holocene. Nevertheless, it is worth noting that natural organic matter is known to accumulate in wetland sediment, formed between the rivers common in Kandal. Therefore, the low-lying topography of this area today seems to depict the boundary of organic-rich Holocene sediments deposited between the rivers. This notion is supported by sediment cores obtained by Quicksall et al. (2008) that identified rapid channel deposition that simultaneously buries both organic matter and the terminal electron acceptors such as Fe and Mn oxides, which drives the in situ dissimilatory reductions of (oxy)hydroxides, thereby releasing sorbed species such as As. "Inefficient flushing" of both As and OM in flat and low-lying areas has been suggested to account for As enrichment in Holocene deltaic aquifers (Smedley & Kinniburgh, 2002; van Geen et al., 2008; Zheng et al., 2004). Perhaps most similar to the MRD is the shallow aquifer of the Hetao Plain of Northern China that consisted of OM-rich, Fe & Mn-oxides-rich and As-rich sediments whereby low hydraulic gradient has been demonstrated to account for the spatial pattern of groundwater As distribution (Zhang et al., 2013).

Findings based on three sediment cores of the MRD are described and compared to shed light on the sedimentation history of MRD formation in the Holocene. Sediment core DT1, penetrating to −51.5 m in the lower MRD of Vietnam (Fig. 4.6), is divided into 5 types of sediments based on mineralogy and lithology excluding the shallowest top soil (Nguyen et al., 2010). At a −45.87 m, the "oldest" silty sediment has a plant material radiocarbon age of 11,643–11,221 years before present (yrs BP) (Ta et al., 2005), suggesting that the sediment core provides constraints for the sedimentation history of MRD in the Holocene (Fig. 4.6). The early Holocene is characterized by coastal marine deposits, with brownish gray silty clay and sandy silt interbedded with very fine sand between altitudes of −36 and −51.5 m representing marsh/tidal flat sediment facies, with a sediment sample from −34.07 m showing an apparent radiocarbon age of 10,725–10,370 yrs BP (Ta et al., 2005). It is worth noting pebbles are identified from −30 to −40 m, suggesting sediment deposition by fast flowing rivers able to transport large particles. The next section up (−24 to −35 m) reflects a sub-tidal to intertidal flat depositional environment, consisting of dark gray laminated silty clay and sandy silt, with an apparent radiocarbon age of 9008–8697 yrs BP at the top of this section (−25.41 m) (Nguyen et al., 2010). Peat, rich in organic matter and indicative of a highly reducing sediment depositional environment, is common, and is found at several intervals between −23 and −34 m. With a plant material organic carbon age of 8371–8183 yrs BP (Nguyen et al., 2010), likely reflecting the onset of a mid-Holocene climate optimum with a high global sea level stand (Li et al., 2012; Stattegger et al., 2013), the lower MRD likely had reached the maximum extent of "flooding" and was inundated by the sea for most of the mid-Holocene. With the lowering of sea level in the late Holocene, the sediment exhibits a clear increase in coarsening from silt with interbedded very fine sand at −20 m reflecting pro-delta to very fine sand (−24 to −10 m) reflecting delta front at −13.8 m (Nguyen et al., 2010). By this time in the late Holocene, the delta front had presumably migrated further towards the sea, and the sedimentation environment gradually shifted to intertidal flats and finally, the present-day flood plain.

This sedimentary history is corroborated by two sediment cores (Wang et al., 2018a, 2018b), QTC2 (10°54.329′ N and 105°4.746′ E; elevation: 3 m, depth 20 m) and QTC3 (same location, depth 33 m) in the mid-MRD of Vietnam (Fig. 4.6). QTC3 sediment from a depth of 33 m dated by optically stimulated luminescence (OSL) indicates an age of 19,060–14,680 yrs BP. The most remarkable feature in both sediment cores is the shift from a reducing environment indicated by sediments rich in organic carbon, pyrite and siderite, to an oxidizing environment indicated by Fe(III) oxides at a depth of 7 m in QTC3 (Fig. 4.6). We interpret this as reflecting the late Holocene's lowering sea level that begins to expose the initially reducing sediment to atmospheric oxygen. Given that these two cores are located further upgradient in the MRD than DT1 (Fig. 4.7). this transition may have occurred earlier than what is seen in DT1 Peat (TOC ~ 33.9% w/w) was found only at 16 m in QTC3, providing more corroborative evidence to interpret both sets of sediment records. It is worth noting sediment from the oxidized section at 2 m has an OSL age of 2920–2500 yrs BP. This confirms that the MRD sedimentation is recent.

Avulsion of the Mekong River also influences local sediment depositional environment that creates more prolific aquifers locally, especially in the triangular area between the Mekong and the Bassac Rivers. The first major "tributary" of the Mekong River is the Bassac River, which bifurcates away from the Mekong at Phnom Penh (Fig. 4.1). The area in the upper MRD between these two channels that extends south towards Vietnam marks a triangular region known as the Kandal Province, Cambodia. Kandal, in Khmer language, means between the rivers. Two sediment cores, a channel core (~50 m depth) and a control core (~55 m depth) collected from the Kandal Province along the Bassac River (latitude and longitude information not available) have been interpreted to represent a distinctive sedimentological feature in the upper MRD associated with the avulsion (Quicksall et al., 2008). The "channel" core was drilled in the eastern-most sand bar scroll on the paleo-levee of the avulsed channel, with its aquifer consisting of hydraulically conductive sand from

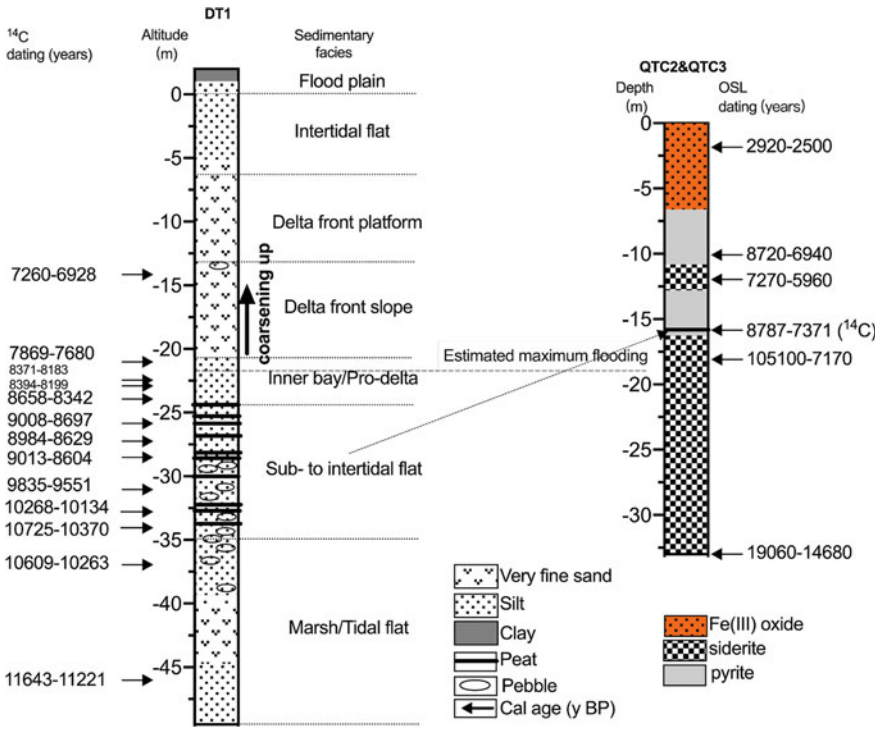


Fig. 4.6 Sediment lithology and facies of DT1 (105°38′51″ E, 10°17′02″ N, depth 51.5 m, elevation +2 m) located in the lower-MRD Vietnam (Fig. 4.6a), with radiocarbon ages of plant materials marked. The redox transition interface at 7.5–11, 13–16 m depth in QTC2 (10°54.329′ N and 105°4.746′ E; elevation: 3 m, depth 20 m) and QTC3 (same location, depth 33 m) in the mid-MRD of Vietnam is interpreted to correspond to the retreating sea level and progradation of the delta front in DT1 starting at ~8.5 kyr BP. The ages for QTC2 and QTC3 consisted entirely of clay and were based on OSL (optically stimulated luminescence) dating of quartz and feldspar in several silicate-rich layers. This figure was adapted from Wang et al. (2018a, 2018b) and Nguyen et al. (2010)

~15 to ~40 m depth. In the MRD of Cambodia (11°31′3.90″ N 105°0′41.77″ E), the horizontal hydraulic conductivity (Kh) of the aquifers' sand was estimated to be $3.15 \times 10^{-4} \pm 3.02 \times 10^{-4}$ m/s based on grain size analysis (n = 14) (Benner et al., 2008). The Kh values of surface clay in MRD of Cambodia were determined by permeameters and slug tests, and were lower, at $4.08 \times 10^{-7} \pm 5.94 \times 10^{-7}$ and $1.22 \times 10^{-6} \pm 1.89 \times 10^{-6}$ m/s, respectively (Benner et al., 2008). In the MRD of Vietnam, Kh values for the aquifers ranged from 0.93×10^{-4} to 2.64×10^{-4} m/s (Minderhoud et al., 2017), based on 999 pumping tests carried out by the Division of Water Resources Planning and Investigation in South Vietnam (DWRPIS, 2010). Based on values on specific aquifer designations by DWRPIS, Kh is assigned to 2.31

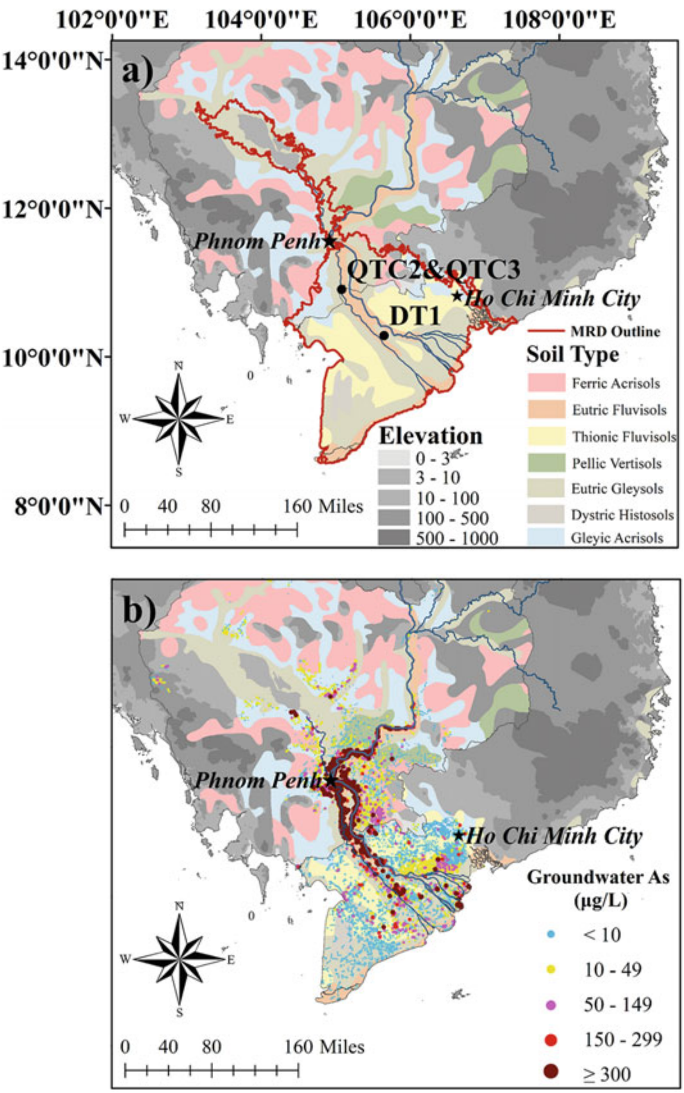
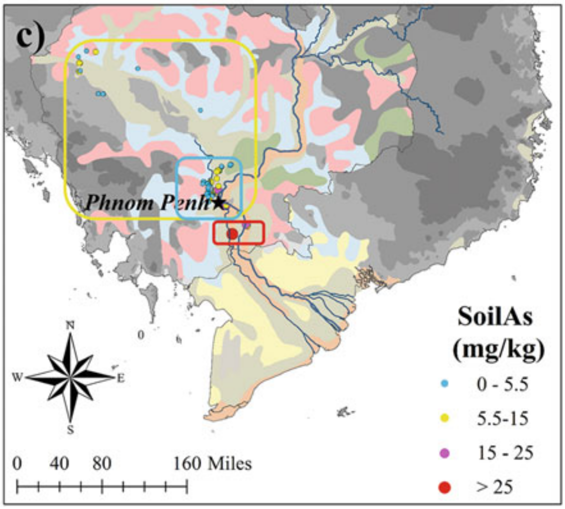
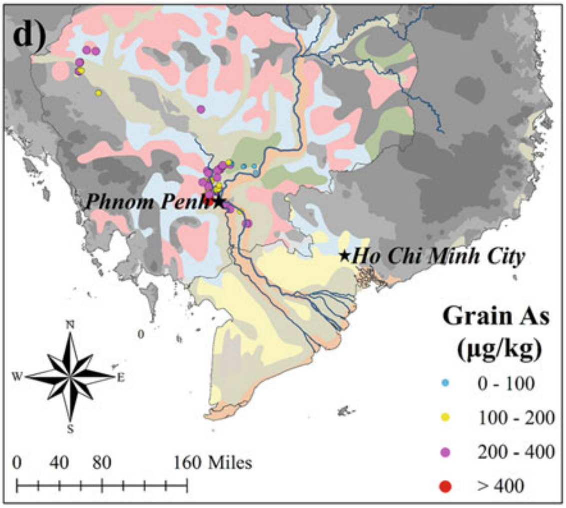


Fig. 4.7 Soil type (**a**), and arsenic in groundwater (**b**), soil (**c**), and rice (**d**) in the Mekong River Delta. **a** Soil type data are from the *Open Development Vietnam* and *Open Development Cambodia*, with 7 types characterized according to the UN FAO Digital Soil Map of the World V3.6 (www.fao.org/geonetworks). The locations of three sediment cores, QTC2&QTC3 (Wang et al., 2018a, 2018b), and DT1 (Nguyen et al., 2010) are superimposed on the elevation and soil type map. The MRD area is outlined in red; **b** Concentration of individual well water arsenic based on 41,928 tests from Cambodia and 52,858 tests from Vietnam as shown in Fig. 4.2a; **c** Soil total As concentration (Table 4.7) are from main rice-growing area collected by Seyfferth et al., 2014 (n = 30, in areas marked by the yellow square) and from a village in Kandal Province with high As in groundwater (n = 15, in areas marked by the red square) (Hamzah et al., 2013), plus our unpublished rice paddy soils (n = 75, northern Phnom Penh, blue square); **d** Arsenic in rice grain data (Table 4.8) are from (n = 30) (Seyfferth et al., 2014) and our unpublished data (n = 95) from the same locations as paired samples of the paddy soil

Fig. 4.7 (continued)





$\times 10^{-4}$ m/s in a model that suggests subsidence due to over draughting of groundwater has caused As release at a deeper depth of MRD of Vietnam (Erban et al., 2013). This intriguing idea has not been followed up by subsequent investigations.

4.4 Arsenic in Soils of the Mekong River Delta

4.4.1 Physiochemical Properties of Soils in the MRD

Over thousands of years, the Mekong River and its tributaries supplied sediments that contributed to soil formation, with an estimated 160 million tons of sediment entering the South China Sea each year (Nguyen et al., 2010). Soils in the MRD are highly variable (Fig. 4.6). Eutric Fluvisol is found to be the dominant soil type occupying ~30% of the MRD, mostly along the banks of the Mekong and Bassac Rivers (Fig. 4.7a). In addition, Eutric Gleysols and Thionic Fluvisols are also common in the lower MRD (for definition of soil types see www.fao.org/geonetworks). Young alluvial, as well acid-sulfate and saline soils reflecting marine influence dominate the deltaic plain (Nguyen et al., 2010). Cambodian soils are primarily clayey loam with 41% of clay plus some gravel (7.9%) based on 103 surface soils sampled across the entire country (Saeki et al., 1959). Along the Mekong River, alluvial soils (42% clay, 4.2% gravel, n = 47) are common in inland basins and are used as paddy rice fields (Saeki et al., 1959).

Blair and Blair (2010) pointed out that 86% of Cambodian soils (n = 3000) contain low organic carbon (0.06–1%), while 63% contain very low total nitrogen (<0.05%) and 88% have low Olsen P (a method that extracts phosphate (PO_4-P) from soils using sodium bicarbonate adjusted to pH 8.5 to assess bioavailability), although the locations of the soil samples in this study may include other areas of Cambodia that are not part of the MRD. Unlike fertile soils in many other subtropical deltas (Wang et al., 2018a, 2018b), soils in the MRD can be poor in nutrients. A survey (Table 4.6) collected 63 soils across Vietnam, nine of which were from the lower MRD, and found that their top soils' (0–20 cm) organic carbon averaged 1.14%, with total nitrogen (TN) averaging 0.11% and P_2O_5 averaging 0.09% (Tran, 2015). Considering the low fertility in the soil and the high demand for crop production, fertilizers, especially mineral fertilizers, were extensively applied to soils in the MRD of Vietnam (UNEP, 2005). There, soils with high iron sulfide (pyrite) are also common. With the oxidation of pyrite by atmospheric oxygen and subsequent release of sulphuric acid, the soil pH has been found to drop below 3 in parts of the lower MRD, forming acid-sulfate soils (Husson et al., 2000).

4.4.2 Soil and Sediment As of the MRD

Arsenic in soils and sediment not only resides in aluminum–silicate minerals but is also associated through adsorption onto amorphous minerals such as Fe–Mn oxides and to a lesser extent, clays (Smedley & Kinniburgh, 2002). Arsenic concentrations in various rocks including sandstone and limestone usually range from <1 to 15 mg/kg, but argillaceous sedimentary rocks such as shales, mudstone and slates can contain much higher As levels of up to 900 mg/kg (O'Neill, 1990). More than 200 minerals

Table 4.6 Physiochemical properties of soil and sediment in MRD of Vietnam and Pearl River Delta

Soil depth (cm)	Total %				pH	EC
	OC	N	P_2O_5	K_2O		(Ms/cm)
Vietnam (n = 63, 9 from MRD)						
0–20	1.14	0.11	0.09	2.47	7.25	1000.0
20–60	0.85	0.10	0.09	2.47	7.45	1000.0
60–85	0.43	0.06	0.07	2.41	7.65	1300.0
85–105	0.62	0.07	0.07	1.99	7.97	1300.0
105–125	0.21	0.04	0.07	1.31	8.20	1100.0
PRD (n = 27)						
0–20	1.68 ± 0.81	0.11 ± 0.04	0.08 ± 0.02	1.75 ± 0.20		

Note Soil OC-Organic Carbon, N-Total Nitrogen and pH etc. (n = 63) in Vietnam were from a slide presented in International Year of Soils (Tran, 2015), although only nine samples were collected from the MRD of Vietnam; Lateritic red soil dominating the Pearl River Delta (PRD) at subtropical latitude is from Wang et al. (2018a, 2018b) and included for comparison

are known to contain various amounts of arsenic, among which, around 60% are in oxyanion form (arsenate) and around 20% are affiliated with sulphur as sulfides and sulfosalts due to the affinity of arsenic to bind with sulphur ligands (Onishi, 1969). Ore geologists have long appreciated the significance of arsenopyrite (FeAsS). It is the most common arsenic mineral found with many sulfide mineral deposits (Boyle & Jonasson, 1973). Because weathering of rocks supplies material to the soil, soil arsenic levels to a large extent reflect the source rock arsenic content, and tend to be elevated in soils adjacent to mining areas, where soil arsenic can reach 4,424 mg/kg (Nriagu et al., 2007). In two sediment cores from the MRD of Vietnam (Fig. 4.6), the authors found that four forms of As existed in the sediment, including sulphur-bound As(III) coupled with natural organic matter (NOM), arsenic in pyrite, oxygen-bound (As(III)) and As(V) (Wang et al., 2018a, 2018b). Arsenian pyrite particles in sediments from 8–16 m have been identified by scanning electron microscopy, with an estimated average As concentration of ~280 mg/kg in pyrite grains (Wang et al., 2018a, 2018b).

Zhang et al. (2017) have demonstrated that each year approximately a quarter of sedimentary As accumulated in the MRD is sourced from upstream geothermal activities that endowed the suspended particulate matter in the Lantsang-Mekong River with elevated As levels. The Mekong River originates from the Tibetan Plateau where it is known as the Lancang River. In Tibet, As enrichment in soils and geothermal water resulting from tectonic activities have been reported (Guillot & Charlet, 2007; Guo et al., 2019; Li et al., 2013; Nordstrom, 2002). Zhang et al. (2017) employed X-ray Absorption Spectroscopy (XAS) to investigate the As and Fe speciation of hot spring deposits and sediments in the Lantcang River in Yunnan Province of China. The study shows that much of the river sediment As is sorbed, with local hot spring deposits containing highly elevated As level of >100 mg/kg. The mobility of As in river sediment is found to be low due to strong arsenate binding to ferric oxides (ferrihydrite, goethite and hematite) and to a lesser extent manganese oxides and clay minerals. The flux of As transported by the Lantsang river sediment (F_{As}) was estimated to be 79.6 ton/year by multiplying the flux of suspended material (FSM, 1850 $\times$ 10^4 ton/year at ChangDu monitoring station) by the average contents of extracted As in sediments (Ex_{As}, 4.30 $\pm$ 1.95 mg/kg). Using the results of radiocarbon dating for sediments in the MRD (Ta et al., 2002) and the average of ~9 mg As/kg in the sediment of the MRD (Polizzotto et al., 2008), the rate of As accumulation in the MRD sediments is estimated to be around 315 ton/year. Thus, about 25% of As in sediments of the MRD each year are coming from upstream geothermal activities. Polizzotto et al. (2008) investigated As levels in the sediment located in the upper reaches of the MRD (Kien Svay District, Kandal Province, Cambodia), reporting ~12 mg/kg As in the youngest sediments near the water table.

A report (Gustafsson & Tin, 1994) measured total As levels by HNO_3/$HClO_4$/H_2SO_4 digestion of acid sulfate soils (pH ~ 4) taken from four soil cores in the Plain of Reeds, lower MRD of Vietnam. The total As levels ranged from 6–41 mg/kg with a mean of 11 $\pm$ 2 mg/kg in the top 10 cm soils (Keeney & Nelson, 1982). A later study reported As levels in acid sulfate soils as 1.0 mg/kg after extracting by 0.43 M HNO_3 in sulphidic areas, compared with 0.62 mg/kg in non-acid sulfate soils (Hoaa & Cuong, 2009). These lower values may reflect incomplete dissolution using 0.43 M HNO_3.

In addition to the aforementioned geogenic sources for As in soils and sediment, mining, industry, agriculture and sewage have been known to cause anthropogenic As pollution of soil (Woolson, 1983). It should be noted that their impact tends to be localized in spatial extent. Soil arsenic contamination due to mine tailings, smelting of non-ferrous metals, and burning of As-rich coals have been well documented at numerous sites around the world (Han et al., 2003). The global annual amount of arsenical pesticides applied in orchards was estimated to be 7–11 $\times$ 10^3 ton-As in 1983 (Woolson, 1983). Until the banning of arsenical pesticides in 2004 by the US Environmental Protection Agency (EPA), they elevated As level in soils to as high as 2,500 mg/kg (Bencko & Foong, 2017). An arsenical, 3-nitro-4-hydroxyphenylarsonic acid (Roxarsone), along with other phenylarsonic compounds, were widely used (Chapman & Johnson, 2002) as feed additives for animals around the world since the 1930s and 1940s (Hanson et al., 1955; Morehouse & Mayfield, 1946), leading to elevated As levels in chicken and chicken poops (Nachman et al., 2013) which contain a proportion of carcinogen, inorganic arsenic (iAs) after biotransformation in soil (Yang et al., 2016). Therefore, it further contaminated the soil, where poultry litter was used as fertilizers to grow crops (Ashjaei et al., 2011) and vegetables (Yao et al., 2009). In February 2014, the US Food And Drug Administration (FDA) formally withdrew the approval of Roxarsone after detecting high levels of iAs in the livers of chickens fed with Roxarsone additives, followed by a ban of any arsenical additives for animals on April 1st, 2015 (FDA, 2015). China also banned the use of any phenylarsonic feed additives on May 1st, 2019 (Hu et al., 2019).

Anthropogenically sourced As in soils of the MRD is minor and highly localized compared to natural sources. A recent study (Olson & Cihacek, 2020) pointed out that arsenical pesticides, especially Agent Blue (cacodylic acid, $C_2H_2AsO_2$), were extensively used during the American Vietnam War (1965–1972) to destroy rice growth. It is estimated that at least 1 million kg As in the form of Agent Blue was added aerially to the MRD and Central Highlands of South Vietnam to destroy mangrove forests and rice paddies. To the best of our knowledge, no measurements of Agent Blue in the soils of South Vietnam are available, so the impact remains not possible to assess.

The most relevant to rice As and subsequent health risk assessment is paddy soil As, with observations suggesting that irrigation with groundwater rich in As has increased paddy soil As concentrations (Fig. 4.8). Several studies have investigated paddy soil As in the MRD (Table 4.7). In the MRD of Cambodia, Hamzah et al. (2013) measured soil samples from 15 locations in Phumi Khleang, Kandal Province. The concentration of total As in soil ranged from 5.3 to 27.8 mg/kg, with a mean of 9.9 ± 5.4 mg/kg. A subsequent study investigated 23 matching paddy rice soil (0–20 cm) and rice samples from five major rice-growing areas of Cambodia including Battambang, Banteay Meanchey, Kampong Thom and Siem Reap Provinces, and Kandal Provinces (Seyfferth et al., 2014). The concentration of tAs in soil ranges from 0.8–18 mg/kg with a mean of 7.8 ± 4.6 mg/kg As. In addition, soils from Banteay Meanchey and Battambang provinces from the northwestern area around Tonlé Sap have lower As concentrations than those from the Kandal and Prey Veng Provinces close to the Mekong River. Due to the paucity of paired soil and rice As analysis, we included our unpublished data of bulk As concentrations in 75 paddy rice soil samples collected from the upper Mekong River Delta in Cambodia determined by X-ray Fluorescence Spectrometer (XRF) with a detection limit of 2.4 mg/kg (DiScenza et al., 2014) (Table 4.7). They are collected mostly around Phnom Penh (Fig. 4.7c), ranging from northwestern Kandal to Kampong Cham with an average of 3.7 ± 3.5 mg/kg total As in soil. The maximum value of 18 mg/kg is detected for a soil sample from northwestern Kandal irrigated by groundwater containing 317 µg/L As (PP119-41-Soil, 11°43′46.4″ N 104°54′40.0″ E). Soils from the west side of Khan Preaek Pnov Lake in Phnom Penh contain lower As (1.9 ± 1.4 mg/kg As, n = 43), while soils from Kandal contain higher As (10.3 ± 2.8 mg/kg, n = 12).

A cumulative frequency plot of our soil data together with the literature data (n = 117) (Hamzah et al., 2013; Huang et al., 2016; Seyfferth et al., 2014) shows that 7.7% of all soil samples exhibit above 12 mg/kg of As, the Vietnamese standard for soil maximum contaminant level (Fig. 4.8). Among them, our unpublished Cambodian soil data displayed the lowest levels of As (3.7 ± 3.5 mg/kg, n = 75) and none of them exceeded 12 mg/kg except one paddy rice soil sample from Kandal irrigated with high-As groundwater. That high-As groundwater irrigation leads to paddy soil As enrichment is consistent with that all of 20% of 30 soil As samples exceeding 12 mg/kg are from Kandal (n = 5) and Prey Veng (n = 1) Provinces, documented by Seyfferth et al. (2014). In a village of Kandal Province with known high-As groundwater occurrence, 13% of 15 paddy soil samples (9.9 ± 5.4 mg/kg) were found to exceed 12 mg/kg As (Hamzah et al., 2013), possibly reflecting

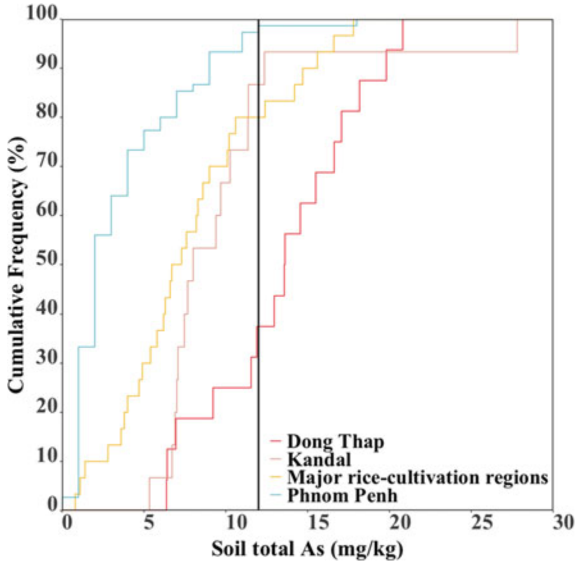


Fig. 4.8 Cumulative frequency distribution of soil total As concentrations in the MRD (Table 4.5). The samples are 30 paddy rice soils from the main rice production areas of Cambodia (Seyfferth et al., 2014), 15 soil samples from groundwater-As affected Phumi Khleang village, Kandal Province of Cambodia (Hamzah et al., 2013), 75 paddy rice soil samples from north Phnom Penh, Cambodia collected by us, with locations marked in Fig. 4.7c. An additional 16 agricultural soils from (Huang et al., 2016) in Thanh Binh district of Dong Thap Province of Vietnam are included here, although the exact locations are not available. The samples in (Seyfferth et al., 2014) were from Banteay Meanchey (n = 8); Battambang (n = 10); Kandal (n = 5); Kampong Thom (n = 1); Prey Veng (n = 5); Siem Reap (n = 1). The Maximum Contaminant Level (MCL) for soil total As in Vietnam is shown as the thick black line

local variabilities although groundwater used for irrigation was not analysed for As, making it impossible to examine the linkage. Fortunately, in the MRD of Vietnam, Huang et al. (2016) investigated 16 soils irrigated by groundwater in Thanh Binh district of Dong Thap Province, observing a positive correlation between As concentrations in groundwater (448 ± 257 μg/L) and matching soil samples, with 62.5% of samples with As levels exceeding 12 mg/kg (mean 13.4 ± 4.6 mg/kg). Finally, a recent study surveyed 80 matching paddy rice soils and rice samples in the lower MRD of Vietnam and determined the average As levels of soil as 12.6 ± 3.2 mg/kg, with the maximum reaching 28.9 mg As/kg (Nguyen et al., 2020), although the soil As data were not available for tabulation, with groundwater As status unknown.

We are aware that nations have set different soil As standards, although the science behind such standards has room for improvement, especially given the uncertainty of soil As bioavailability and uptake by rice as described below. For example, the Japanese standard for As in paddy soil is 15 mg/kg and while the As critical upper limit set by Chinese authorities for paddy soil is 20–30 mg/kg depending on soil pH (GB 15618-2018). In light of such uncertainties, the elevated As in rice paddy

Table 4.7 Concentration of soil total arsenic from the Mekong River Delta of Cambodia and Vietnam

Location	Min	Max	Median	Mean	SD	n	References
	(mg/kg)						
Vietnam							
Dong Thap	6	21				17	Huang et al. (2016)
MRD	8.3	28.9	12.4	12.6	3.2	80	Nguyen et al. (2020)
Cambodia							
Banteay Meanchey	1.4	9	6.6	6.2	2.4	9	Seyfferth et al. (2014)
Battambang	2.8	8.2	4.9	5.2	1.7	9	Seyfferth et al. (2014)
Kampong Thom				1.1		1	Seyfferth et al. (2014)
Kampong Cham	2	4	2.5	2.7	0.8	6	Unpublished data*
Kampong Chrang	4	11	6.5	6.9	2.2	8	Unpublished data*
Kandal	10.3	27.8	13.3	14.9	5.1	20	Hamzah et al. (2013), Seyfferth et al. (2014)
Phnom Penh	<1	18	2	3.1	3.4	62	Unpublished data[a]
Prey Veng	8.3	15.6	10.2	11	2.7	5	Seyfferth et al. (2014)
Siem Reap				0.8		1	Seyfferth et al. (2014)
Total	<1	28.9		6.45		218	

Note "/" means data cannot be acquired
[a] Unpublished data are from the authors, with bulk soil As concentrations determined by XRF (see text)

soils of the lower MRD in Vietnam and Cambodia deserves closer scrutiny. This is discussed below from the perspective of rice yield briefly, as well as bioavailability and toxicity of rice arsenic in the rest of this chapter.

A consideration for setting soil As standard is to safeguard rice yield. Association between soil As content and the incidence of straighthead diseases was observed for applications of monosodium methanearsonate (MSMA) (Horton et al., 1983), which has led to poorly developed panicles and a reduction in rice yield between 24 and 96% depending on rice varieties (Yan et al., 2005). A lab study found that when soil tAs was greater than 50 mg/kg, the extent of straighthead diseases was severe in rice, with a dose–response relationship of a yield reduction from 100% to only 16%

when soil tAs increased from 50 to 90 mg/kg by addition of As(V) solutions to soils (Rahman et al., 2008). Rice yield was found to negatively correlate with the soil tAs concentration ranging from 10 to 70 mg/kg in paddy soils irrigated by groundwater with 130 μg/L of As in Bangladesh (Panaullah et al., 2009), with each 10 mg/kg soil tAs increase corresponding to about 2 ton/ha loss in yield. This highlights the need to move away from irrigation using high-As groundwater.

4.4.3 The Linkage Between Paddy Soil and Rice As Speciation

As speciation in paddy soils is of interest because the differences in chemical properties of various As species influence the bioavailability of As to plants, especially during the uptake of arsenic by plant roots. Unfortunately, hardly any study has assessed soil As speciation in the MRD. A study compared soil arsenic speciation between control sites and sites subject to solid wastes in Vietnam (Le et al., 2011). It revealed that most As in soil are inorganic. In aqueous solutions and at neutral pH, inorganic As (iAs) species arsenate (As(V)) is mostly $H_2AsO_4^-$ with a pKa_1 of 2.19 under oxidizing conditions while iAs species arsenite (As(III)) is mostly H_3AsO_3 with a pKa_1 of 9.23 under reducing conditions (Cullen & Reimer, 1989). Das et al. (2016) reported that 87–94% of As was As(III) in flooded (reducing) soils while 73–96% of the total As was As(V) in aerobic soils, indicating that the speciation of As is regulated by redox reactions in soils which can be affected by irrigation practice. In most contaminated soils, iAs species are the dominant forms (Nriagu et al., 2007).

Among major crops, rice is of particular concern due to its high shoot assimilation rate for As compared to wheat and barley (Williams et al., 2007). In general, rice plants cultivated in soils with higher solid As concentrations are found to uptake more As due to higher dissolved pore water As concentrations in the rhizosphere (Suriyagoda et al., 2018). In addition to soil total As concentration (Bogdan & Schenk, 2009), a wide range of soil parameters, including texture, pH, iron (Fe) (hydr)oxides (Chen et al., 2005), plant-available phosphorous (P) (Cheng et al., 2004), plant-available silicon (Si) (Amaral et al., 2017), and sulphur (S) (Zhao et al., 2010) have been found to affect the uptake of arsenic by rice. Campbell and Nordstrom (2014) found that soil pH is significantly correlated with the concentrations of total As in rice, because high pH increases negative surface charges of soils, which in turn promotes the desorption of As(III) and As(V). Fu et al. (2011) demonstrated that soil organic matter negatively correlated with total As in rice grains, which may result from the formation of insoluble complexes between organic matter and As, making As less bioavailable to rice plants (Wang & Mulligan, 2006). On the other hand, because dissolved organic matter competes for adsorption sites on Fe(III) (hydr)oxides via ligand exchange with both As(III) and As(V), it may increase mobility and bioavailability of As(III) and As(V) (Wang & Mulligan, 2006). Due to the high affinity of As to soil Fe(III) (hydr)oxides, its role is noteworthy and it has been shown that this is a key process responsible for lowering As uptake by rice (Lauren & Duxbury, 2005). The formation of soil Fe(III) (hydr)oxides is aided by the rice plants. The radial oxygen transported from root tissues to the surrounding soil allows for a micro-oxygenated environment in the soil, with the formation of Fe plaque on the surfaces of the rice root, effectively "blocking" the As from entering the root (Hossain et al., 2009).

Once As overcomes the Fe plaque barrier ubiquitously present on rice roots, the uptake mechanisms of iAs have been a topic of intense interest over the past two decades, with phosphate-P and silicate-Si transporters found to be important. Being in the same Group in the Periodic Table, and thus with similar chemistry, As(V) uptake by P transporters in rice has been demonstrated. Therefore, there is a competition between As(V) and P for the uptake of both. Although P can mobilize adsorbed As(V) in minerals to increase available As to plants (Peryea, 1991; Sadiq, 1997), high plant-available P also decreases As(V) uptake through competition (Jiang et al., 2014; Meharg & Macnair, 1990) and suppressing the P transporters (Finnegan & Chen, 2012). High levels of silicic acid have been shown to reduce As(III) uptake in plants (Bogdan & Schenk, 2009; Desplanques et al., 2006; Guo et al., 2005, 2007; Ma & Takahashi, 2002; Seyfferth & Fendorf, 2012; Seyfferth et al., 2016b). Due to the similar structure of silicic acid and As(III), large quantities of Si suppress the expression of transporters, *Lsi1* and *Lsi2* (Ma et al., 2006), resulting in overall low As(III) uptake. Finally, S levels in soil affect the As uptake especially As(III), most likely due to the binding of thiol-group chemicals to As(III) thus reducing the translocation of it from root to grain (Zhao et al., 2010).

Soil microorganisms also play an important role in As uptake by rice, especially the uptake of methylated As; this is because to date no evidence exists to support methylation of As by rice plants (Lomax et al., 2012). Microorganisms in paddy soils are involved in the As biotransformation through different pathways (Zhang et al., 2015a, 2015b). Not only do they regulate oxidation and reduction between As(III) and As(V), but also they are involved in methylation and demethylation reactions between inorganic and organic forms of As (Qin et al., 2006; Yoshinaga et al., 2011). The gene responsible for microbial oxidation of As(III) to As(V) has been identified as *aioA* gene (Hamamura et al., 2009). Two genes, *arsC* and *arrA,* are both able to reduce As(V) to As(III) in paddy soils in different pathways (Malasarn et al., 2004). While the *arsC* and *arrA* regulated reduction usually occurs under flooded (anaerobic) conditions, phylogenetically diverse bacteria have been shown to reduce As(V) under non-flooded (aerobic) situations (Bachate et al., 2009). *arsM* is responsible for converting iAs to methylated As including MMA(III), MMA(V), DMA(III), DMA(V), TMAs(V), and TMA(III) (Challenger, 1945; Qin et al., 2006). Microbial As methylations were first found in fungi *Scopulariopsis brevicaulis* (Challenger & Higginbottom, 1935), and then other bacteria and methanoarchaea were reported with the ability to volatilize As by methylation (Wang et al., 2014). Zhao et al. (2013a, 2013b) used GeoChip to identify *arsM* sequence in six soils, observing a positive correlation between soil pH and *arsM* abundance.

4.5 Health Risk Assessment of Rice Arsenic Exposure in the Mekong River Delta

4.5.1 Arsenic in Foodstuff

Concerns have been raised on the toxicity of arsenic in food in the last decade, especially when rice is used as transition food for infants (Carignan et al., 2016). Because the crustal abundance of As, at 2.5 mg/kg, is not low (Rudnick & Gao, 2003), and that amorphous and clay minerals in soil can sorb large amounts of arsenic, soils are naturally endowed with arsenic at levels of ~5 mg/kg (ATSDR, 2007). In addition, the loading of As from irrigation by groundwater enriched in As further enhances soil As levels (Khan et al., 2010). Therefore, the risks for uptake and bioaccumulation of As by crops cannot be overlooked.

Crops including rice, wheat, corn, legumes, and potatoes have been investigated for total As concentrations, with all exhibiting a great deal of variability. In general, wheat, corn and legumes tend to contain lower levels of As compared to rice. Dozens of studies analysed wheat and determined bulk As concentration ranging from 10–500 μg/kg with a mean of <100 μg/kg (Adomako et al., 2011; Shi et al., 2015; Williams et al., 2007). In the following, all food As concentrations are reported in dry weight unless noted. Corn was reported to display As concentrations ranging from 10–170 μg/kg in Tanzania (Marwa et al., 2012). It is worth noting that a mean of As <100 μg/kg in legumes was detected in market food collected in Bangladesh, although nearly all of this As is iAs, thus concerns regarding its toxicity have been raised (Williams et al., 2006), with similar observations made later in Brazil (Ciminelli et al., 2017). Potato is the fourth largest produced crop (Leff et al., 2004). Potato tuber samples bought from the market displayed a maximum tAs of 890 μg/kg and also 100% iAs in Bangladesh (Williams et al., 2006). Signes-Pastor et al. (2008) later identified MMA in potato tubers from West Bengal with an average of only 80 μg tAs/kg.

Zhang et al. (2015a, 2015b) determined tAs levels in 48 kinds of edible or medicinal mushrooms in Southwestern China, revealing common earthball *Scleroderma citrinum* displaying the highest As (1,700 μg/kg) and *Termitomyces eurrhius* which is a mushroom symbiotic with termites, displaying the lowest As (170 μg/kg). Seyfferth et al. (2016a, 2016b) reported similar tAs levels ranging from 100–1,000 μg/kg in 12 species of mushroom samples (n = 40) collected from the main production areas of the US, with higher As in Cremini (*Agaricus bisporus*) than Shiitake (*Lentinus edodes*). Among 17 samples with tAs >400 μg/kg, iAs accounted for 25–94%, while maximum percentages of 28 and 20% were reported for DMA and AsB respectively.

Williams et al. (2006) collected 94 vegetables from markets around Bangladesh and found that arum stolon had the highest As value of 1,930 μg/kg. Both the mean (343 μg/kg) and the maximum (1,930 μg/kg) As levels for root and tuberous vegetables were higher than those for fruit vegetables (mean: 301 max: 1,590 μg/kg) but not for leafy vegetables (mean: 384 μg/kg and max: 790 μg/kg).

In the MRD, As in food has been investigated by two studies, with concerns raised for areas with high groundwater As and high soil As (Table 4.8). Wang et al. (2013) collected food samples from Kampong Cham, Kratie and Kandal Provinces in Cambodia along the Mekong River with low (1.3 ± 0.6 μg/L), medium (22 ± 44 μg/L), and high (846 ± 298 μg/L) levels of groundwater As (Phan et al., 2010), respectively. A food frequency questionnaire was used to acquire consumption patterns among residents surveyed in Kratie (n = 31), Kampong Cham (n = 58), and Kandal (n = 69) Provinces; it revealed a high proportion of rice intake (46.8%), followed by vegetables (23.8%), fruits (13.5%), and fish (10.2%), with a small percentage of meat (3.11%) and viscera (1.73%). A total of 154 food samples and 22 food products were collected and measured after removing inedible parts, freeze-drying, and grounding. Most food samples collected from Kandal Province contain higher As levels than those from Kratie and Kampong Cham Provinces. The highest As levels of all food samples were detected in fish from Kandal with a mean of 2,832 ± 1,606 μg/kg (n > 9) in wet weight (ww). The lowest As levels were detected in cattle stomachs from Kratie with 1.86 ± 1.10 μg/kg (n = 3) in ww. The rice samples from Kandal also contain significantly elevated As (247 ± 187 μg/kg, ww) than samples from Kampong Cham (29 ± 24 μg/kg, ww). Meat such as beef (96.7 ± 9.9 μg/kg, ww) and egg (64.2 ± 85.5 μg/kg, ww) tend to contain higher As levels than vegetables, fruit and viscera. However, a vegetable (Morning Glory) collected from Kandal showed a higher mean As of 277 ± 80 μg/kg, ww.

Phan et al. (2013) conducted a similar study in Kampong Cham, Kratie and Kandal Provinces of Cambodia (Table 4.8). Besides food samples, they also collected eight matching paddy soil and rice samples where groundwater was used for irrigation in Kandal and Kampong Cham. Positive correlation between soil bulk As and rice total As was observed with a Pearson correlation coefficient of 0.826 ($p < 0.01$). The total As in uncooked rice (256 ± 141 μg/kg) and soil (12.9 ± 10.4 mg/kg) from Kandal were significantly higher than those from Kampong Cham (24 ± 12 μg/kg in rice, 0.8 ± 0.1 mg/kg in soil), evaluated by an independent *t*-test ($p < 0.05$). The tAs in food, including uncooked rice, fish and vegetables from these three provinces were significantly different by One-Way ANOVA (Tukey HSD and Games-Howell, $p < 0.05$), with the highest in Kandal, followed by those from Kratie and the lowest in Kampong Cham.

One important implication of the Phan et al. (2013) study emerges when the As levels in groundwater used for irrigation are considered. In Kandal, rice paddy soil with on average >12 mg/kg As (Vietnamese soil MCL) producing on average >200 μg/kg tAs in uncooked rice (WHO standard for iAs in rice is 200 μg/kg) is probably irrigated by groundwater with on average 846 ± 298 μg/L of As (n = 46) (Phan et al., 2010), although the exact groundwater As concentration used for irrigation was not reported in Phan et al. (2013). Therefore, this one study would support setting a soil As standard for MRD soil at 12 mg/kg, although more studies would be necessary to enhance the science. It also underscores the urgency to shut down high-As wells used for irrigation in the region. It is reassuring that in Kampong Cham where irrigation relies on low-As groundwater (1.3 ± 0.6 μg/L, n = 18, (Phan et al., 2010)) and rainwater, neither paddy soil nor rice showed any evidence of As

Table 4.8 Total arsenic concentrations (µg/kg) in food items from the Mekong River Delta of Cambodia

Foodstuffs	Kandal			Kratie			Kampong Cham		
Reference	Mean ± SD	Median	Range	Mean ± SD	Median	Range	Mean ± SD	Median	Range
(Phan et al., 2013) in dry weight									
Rice									
Uncooked (n = 10)	256 ± 141	231	88–578	75 ± 49	61	12–171	24 ± 12	2	14–48
Cooked (n = 10)	255 ± 343	135	10–1.189	79 ± 57	73	5–190	12 ± 11	7	4–31
Fish									
Catfish (n = 5)	148 ± 4	147	144–155	86 ± 2	85	84–88	77 ± 5	76	71–83
Snakehead (n = 5)	209 ± 13	216	193–222	2.918 ± 1.605	3.424	94–3.993	82 ± 1	83	81–83
All (n = 10)	178 ± 34	174	144–222	1.502 ± 1.837	91	84–3.993	80 ± 4	81	71–83
Vegetable									
Cucumber (n = 3)	131 ± 9	128	123–141				85 ± 46	66	53–137
Gourd (n = 3)	43 ± 17	33	32–62	26 ± 4	23	23–31	17 ± 6	18	10–21
Papaya (n = 3)	89 ± 42	93	45–128	26 ± 14	19	16–42	20 ± 3	21	17–22
Pumpkin (n = 3)	11 ± 2	1	10–13	9 ± 5	7	4–14	22 ± 15	18	9–38
Tomato (n = 3)	35 ± 13	43	20–43				25 ± 12	23	14–38
All (n = 15)	62 ± 48	43	10–141	20 ± 12	19	4–42	34 ± 33	21	9–137
(Wang et al., 2013) in wet weight									
Vegetable									

(continued)

Table 4.8 (continued)

Foodstuffs	Kandal			Kratie			Kampong Cham		
Reference	Mean ± SD	Median	Range	Mean ± SD	Median	Range	Mean ± SD	Median	Range
Bitter guard							17.4 ± 6.03	15	13–24.3
Cabbage	20 ± 7.96	20.4	11.8–27.7	5.18 ± 0.45	5.26	4.69–5.59	19.8 ± 2.42	20.8	17–21.5
Carrot							37 ± 1.54	37.5	35.3–38.2
Chinese radish				2.57 ± 0.27	2.48	2.35–2.87	22 ± 1.34	22.6	20.5–23
Cucumber	55.2 ± 18.4	54.6	37.1–74				12.3 ± 2.55	11.3	10.5–15.2
Eggplant	10.3 ± 2.99	11.9	6.89–12.2						
Long bean				3.93 ± 0.49	3.77	3.54–4.47	19.6 ± 1.73	20.5	17.6–20.6
Morning Glory	277 ± 79.9	252	214–367	40.6 ± 5.33	38.4	36.8–46.7	57 ± 8.37	61.6	47.3–62.1
Mustard green							6.8 ± 1.15	6.73	5.69–7.99
Petsai				8.69 ± 1.76	7.68	7.66–10.7	5.43 ± 0.97	5.35	4.5–6.43
Sponge gourd	23.3 ± 12.8	29.9	8.54–31.5				11.2 ± 0.64	11.1	10.7–11.9
Winter melon	10.5 ± 5.28	8.28	6.7–16.5	5.63 ± 1.68	5.72	3.9–7.26	7.18 ± 2.72	6.76	4.7–10.1
Rice	247 ± 187	224	13.8–649				29.1 ± 24	25.1	8.38–85.2
Fruits									
Banana							13.1 ± 1.58	13.8	11.3–14.2
Fish	2832 ± 1606	2237	1609–4650	8.11 ± 3.66	9.55	3.95–10.8	495 ± 135	520	349–616
Meat									
Beef	96.7 ± 9.92	97.9	86.3–106	4.1 ± 4.93	2.44	0.22–9.64	63.8 ± 6.29	61.4	59.1–71
Pork				11.7 ± 2.96	10.6	9.47–15.1	19.3 ± 11.8	15.2	10.1–32.5
Egg	64.2 ± 85.5	24.1	6.05–162				22.6 ± 18.2	27.9	2.32–37.4

(continued)

Table 4.8 (continued)

Foodstuffs	Kandal			Kratie			Kampong Cham		
Reference	Mean ± SD	Median	Range	Mean ± SD	Median	Range	Mean ± SD	Median	Range
Viscera									
Cattle heart							4.38 ± 5.03	1.87	1.11–10.2
Cattle kidney	234 ± 32.9	216	213–272						
Cattle liver	12 ± 2.62	11.3	9.76–14.9				9.55 ± 5.6	11.8	3.17–13.6
Cattle stomach				1.86 ± 1.1	2.26	0.62–2.7			

enrichment. According to the locations of rice grains, we divided them into two groups. One is collected from areas with high-As groundwater and the other is from areas with low-As groundwater. The tAs of grains (277 ± 127 μg/kg, n = 112) from areas likely irrigated by high-As groundwater was higher than those from areas using low-As water for irrigation (177 ± 84 μg/kg, n = 95) ($p < 0.001$, LSD, One-Way ANOVA). It should be noted that in areas with frequent high-As groundwater occurrence, there are still local spatial variabilities so not all irrigated groundwater has high As.

4.5.2 Arsenic in Rice Grains

According to a European foodstuff survey by the EFSA (European Food Safety Authority) (EFSA, 2009), rice grains (n = 1,122) contain much higher As levels (Mean: 136 μg/kg, Median: 110 μg/kg, 95th percentile: 360 μg/kg, Max: 1180 μg/kg) than other major crops (n = 2,215) (Mean: 14.7 μg/kg, Median: 0 μg/kg, 95th percentile: 60 μg/kg, Max: 5662 μg/kg). This survey lends support for that As in rice grains is a significant contributor to dietary As intake by humans in populations not exposed to iAs from drinking water.

The tAs concentrations in rice grains show great variations among different varieties, cultivation methods and locations. Meharg et al. (2009) analysed tAs of 901 rice grains collected from markets of ten countries. The mean of tAs values varied sevenfold among countries, with the highest mean tAs of 280 μg/kg detected in France (n = 33) followed closely by the mean tAs of 250 μg/kg detected in the US (n = 163). Rice grains from Spain also contained relatively high tAs (Mean: 200 μg/kg, n = 76). Surprisingly, rice grains from Asian countries including China, Thailand and Bangladesh contained relatively low tAs (Mean: 140, 140 and 130 μg/kg; n = 124, 54 and 144 respectively). The lowest and the second lowest mean tAs were 40 μg/kg in Egypt (n = 110) and 70 μg/kg in India (n = 133), respectively.

Zavala and Duxbury (2008) bought 204 rice samples in New York markets and found that brown rice (usually subject to less milling and retain the bran layer) contained higher tAs (196 ± 111 μg/kg) than usually more thoroughly milled white rice (127 ± 87 μg/kg) did. The concentration of iAs in rice grains varies with the extent of milling because rice husks usually contain higher As concentrations than grains due to the tendency of iAs to accumulate in the outer layers of rice grains (Sun et al., 2008).

We compiled rice grain data (all uncooked unless specifically noted) of the MRD in literature (n = 175, Table 4.9), and expanded this dataset to include 107 rice samples collected by us from northeastern Phnom Penh to western Kampong Cham with one sample from Kandal (Fig. 4.7d). The tAs levels in rice grains of the MRD range from 8 to 788 μg/kg in dry weight with a mean of 197 μg/kg. Two food surveys (Phan et al., 2013; Wang et al., 2013), described above, determined tAs in rice grains from Kampong Cham, Kratie and Kandal Provinces, finding similar levels (Table 4.9). Seyfferth et al. (2014) and Phan et al. (2014) reported tAs in rice grains of

150 ± 60 μg/kg (n = 6) and 201 ± 50 μg/kg (n = 11) in Prev Veng. Because high-As groundwater is likely used for cooking, two cooked rice samples there contained very high levels of tAs of 530 and 600 μg/kg (O'Neil et al., 2013). Seyfferth et al. (2014) surveyed 22 matching paddy rice soil and rice samples from major rice-growing areas of Cambodia (Table 4.7). They found that rice grains from Kampong Thom (260 ± 60 μg/kg), Banteay Meanchey (250 ± 50 μg/kg) and Battambang (195 ± 25 μg/kg) contained higher tAs than those from Prey Veng Province (150 ± 60 μg/kg), even though the soil As level in Prey Veng is higher than those of other provinces. We interpret this as support for the need to further investigate soil As speciation and microbiome that regulate rice As uptake and accumulation in rice grain.

Despite the complexity in soil-rice As linkage, if soil As is sourced from groundwater irrigation, that newly added As may be more bioavailable for rice. For example, Murphy et al. (2018) investigated 16 rice samples from Preak Russey, Kandal Province collected from rice paddies, finding a high average As of 315 ± 150 μg/kg in unpolished husked grain. There is a positive correlation between tAs in those rice grains and their irrigation water ($R^2 = 0.5304$), with As concentration in 16 irrigation water samples ranging from 0 to 1250 μg/L. A study reported average tAs contents in 39 polished rice as 224 μg/kg (132–471 μg/kg) in An Giang province, Vietnam, where groundwater As is high (230, 0.1–997 μg/L) (Hanh et al., 2011). A recent paired soil-rice As survey collected 78 rice samples in the lower MRD of Vietnam, revealing a mean tAs of 180 ± 90 μg/kg with a range from 80 to 560 μg/kg, corresponding to 12.6 ± 3.2 mg/kg of soil As (Nguyen et al., 2020). Like Phan et al. (2013) study discussed earlier, this last study provides additional support for setting soil MCL at 12 mg/kg for Vietnam on the basis of the precautionary principle.

Studies from South Asia also suggest that irrigation using high-As groundwater (>50 μg/L) should be avoided. Due to the anerobic environment of the rice paddy field that facilitates uptake, much attention has been paid to how rice uptakes and accumulates As (Zhao et al., 2010), especially when irrigation water is enriched in As (Rahman & Hasegawa, 2011). Williams et al. (2006) reported higher levels of As in rice grains purchased from regions with elevated As in groundwater of southwestern Bangladesh, with two rice samples from Faridpur containing tAs of 440 and 580 μg/kg irrigated by groundwater with 140 μg As/L. Further, Zavala and Duxbury (2008a) compared As levels in 871 samples of rice grain cultivated in high-As (>6 mg/kg) or low-As (<6 mg/kg) soils, or irrigated with high-As (>50 μg/L) or low-As (<50 μg/L) water in Bangladesh. They found higher mean levels of As in rice grains (242 ± 98 μg/kg) grown in low-As soils but subject to high-As irrigation water, than those (194 ± 74 μg/kg) cultivated also in low-As soils and also irrigated by low-As water. On the other hand, rice grains harvested from high-As soil and irrigated by low-As water exhibited only slight increases (mean: 200 μg/kg, no standard deviation was reported).

Alternative mitigation measures based on soil and crop science to lower the uptake of iAs by rice plants from soils have been explored. For example, by adding highly feasible silicon amendments to rice husks, a 25–50% reduction of iAs in grains has been achieved (Seyfferth et al., 2016b). Other farming practices such as growing rice without long periods of flooding could reduce iAs in grains but could also

Table 4.9 Total arsenic concentrations (μg/kg in dry weight) in rice grains from several provinces of Vietnam and Cambodia

Province	Min	Max	Mean	SD	No	References
Vietnamese raw rice grain						
Mekong River Delta	80	560	180	90	78	Nguyen et al. (2020)
Cambodian raw rice grain						
Banteay Meanchey	153	280	250	50	8	Seyfferth et al. (2014)
Battambang	146	239	195	25	10	Seyfferth et al. (2014)
Kampong Cham	14	48	24	12	10	Phan et al. (2013)[b]
Kampong Cham	8	85	29	24	3	(Wang et al. (2013)[c]
Kampong Cham	48	323	189	85	23	Unpublished data[d]
Kampong Chnang	216	328	260	60	3	Unpublished data[d]
Kampong Thom			371		1	Seyfferth et al. (2014)
Kandal	96	270	158	33	22	Murphy et al. (2018)
Kandal	130	298	200	80	6	Seyfferth et al. (2014)
Kandal	14	649	247	187	3	Wang et al. (2013)[c]
Kandal	88	578	256	141	10	Phan et al. (2013)[b]
Kandal			264	83	1	Unpublished data[d]
Kratie	12	171	75	49	10	Phan et al. (2013)[b]
Phnom Pehn	9	788	173	123	80	Unpublished data[d]
Preak Russey[a]	107	578	315	150	45	Murphy et al. (2018)
Prey Veng	100	245	150	60	6	Seyfferth et al. (2014)
Prey Veng	91	285	201	50	11	Phan et al. (2014)
All Cambodian raw rice grain	**8**	**788**	**197**	**360**	**252**	
Vietnamese cooked rice grain						
An Giang	132	471	224		39	Hanh et al. (2011)
Cambodian cooked rice grain						
Kampong Cham	4	31	12	11	10	Phan et al. (2013)[b]
Kandal	10	1189	255	343	10	Phan et al. (2013)[b]
Kratie	5	190	79	57	10	Phan et al. (2013)[b]
Prey Veng	530	600	565	49	2	O'Neil et al. (2013)
All Cambodian cooked rice grain	**4**	**1189**	**228**	**351**	**32**	

[a]Rice irrigated by high-As groundwater
[b]Phan et al. (2013) collected pair raw rice and cooked rice and showed no significant difference (Pair-t test)
[c]Wang et al. (2013) reported As levels in rice grains as wet weight
[d]Unpublished rice tAs data of the authors are measured by ICP-MS measurements followed by nitric acid digestion. Rice samples were collected from paddy soil irrigated mostly by low-As water except the one in Kandal, with the husk removed

cause lower yields and elevated cadmium (Beans, 2021). Another approach is to develop genetically modified rice cultivars with substantially lower As uptake, yet identification of such genes remains a challenge after over a decade of work. Recently, the team of Fang-jie Zhao has identified a genetic mutation that led to a decrease of As in rice grain by one third, albeit indirectly (Sun et al., 2021).

4.5.3 Arsenic Speciation in Rice Grains

Assessment of human health risks due to As exposure from rice must consider the As speciation in rice grains. Rice grains are also known to contain significant amounts of methylated oxyarsenates, mainly as dimethylated arsenate (DMA(V)), which is known to be far less toxic than iAs (Ng, 2005). Most rice grains contain over 50% of As as iAs except for those produced in the USA (Rahman & Hasegawa, 2011; Williams et al., 2005). Recently, a study detected a highly toxic thiolated As, demethylated monothioarsenate (DMMTA) in rice grains from 15 countries, with DMMTA up to 21% of tAs (Dai et al., 2022). In the following section, chemical extraction based As speciation assay of rice grains is summarized to provide the background necessary to understand the uncertainties remaining in health risk assessments of rice arsenic exposure described in the next Sect. 4.5.4.

Chemical extraction of rice followed by separation using chromatography and As detection (Kubachka et al., 2012) has identified iAs and DMA(V) as the dominant As speciation in 95 market rice samples collected from seven countries (Meharg & Zhao, 2012). The aforementioned EFSA report conducted 706 speciation measurements on European rice grains (EFSA, 2014), reporting mean iAs levels as 101 μg/kg and 95th percentile iAs as 197 μg/kg, with the average of brown rice (152 μg/kg) higher than that of white rice (89 μg/kg). This is consistent with an earlier study (Williams et al., 2005) that analysed As speciation of 51 market rice samples from North America (Canada, US), Europe (Italy, Spain), Asia (Taiwan, Thailand, India), and from Bangladesh, with the US rice grains showing lower %iAs ($42 \pm 5\%$, $n = 12$) than Asian rice grains including Bangladeshi ($80 \pm 3\%$, $n = 11$) and Indian ($81 \pm 4\%$, $n = 15$) grains. Rice grains in the US tend to have more DMA(V), averaging $49 \pm 17\%$. A subsequent compilation of all the acquired speciation data from seven countries ($n = 95$) showed that the average %iAs in rice is around 54% of the total As (Meharg & Zhao, 2012), with 21.5% as DMA(V).

Depending on location of cultivation, the same rice cultivar can have a wide range of As concentrations as well as percentages of iAs and DMA(V) with reasons not fully understood at present (Williams et al., 2005; Zavala et al., 2008). Not enough is known regarding the mechanisms of uptake and metabolism of arsenic by rice plants to conclusively predict which rice cultivar will have more toxic iAs or less toxic DMA(V) in the grains, even when they are subject to the same soil and growth conditions. In pot experiments to investigate the influence of rice genotypes and soil As on As speciation of rice grains, it has been shown that under the same conditions of cultivation, %DMA of rice grain varies from 7 to 56% (Williams et al., 2005).

In this experiment, soil As was amended with monosodium arsenate to result in an increase of soil tAs concentration from 31.3 to 100 mg/kg (soil As speciation was not assessed in this pot experiment). The soil As and rice As speciation linkage is complex (Zhao et al., 2010, 2013a, 2013b) and is a subject of intense ongoing research. For example, a recent study (Dai et al., 2021) detected methylated thioarsenate species in soil porewaters and rice, identifying 0.4–10.1 μg/kg highly toxic dimethylated monothioarsenate (DMMTA) in rice grains, of which bioavailability is still unknown.

Concentration and speciation of As are heterogenous in a single rice grain at microscopic scale. In addition to the well-established rice husk being enriched in tAs (Rahman et al., 2007), iAs levels in rice bran (~1000 μg/kg) can be much higher than that in rice grain by 10–20 fold in whole grain rice samples collected from China and Bangladesh (Sun et al., 2008). Although in situ speciation analysis relying on non-destructive synchrotron techniques are still few, grain arsenic probed by micro-X-ray absorption near edge structure (μXANES) reveals that most iAs is As(III) and is located in ovular vascular trace, while the DMA(V) distributes more evenly from external grain parts to endosperm (Carey et al., 2010).

Murphy et al. (2018) collected well water (n = 65) and matching soil (n = 70) and rice samples (n = 105) in Preak Russey, Kandal Province, following a chemical extraction to detect %iAs and %DMA(V) in rice grains with an average value of 80 ± 13 and 21 ± 13% respectively (n = 55). A follow-up study (Murphy et al., 2020) collected 10 rice samples irrigated by well water from a control area with lower As (103 ± 175 μg/L) in groundwater to compare with rice collected in Preak Russey (groundwater As 953 ± 349 μg/L). It is not surprising that Preak Russey rice grains irrigated by high-As groundwater contain higher As(V) (174 ± 45 μg/kg, n = 57) and DMA(V) (124 ± 111 μg/kg, n = 57) concentrations than those irrigated by low-As groundwater, with lower rice As(V) of 111 ± 29 μg/kg and DMA(V) of 40 ± 31 μg/kg. Combining the 112 As speciation data points from these two studies in Kandal, MRD of Cambodia (Murphy et al., 2018, 2020), a negative correlation between %iAs and tAs and a positive correlation between %DMA(V) and tAs emerged from this dataset, implying that rice is protecting themselves by translocating more methylated As into grain when As uptake is higher (Fig. 4.9). The mean iAs concentration in rice grains reported by the two Murphy papers is 200 ± 61 μg/kg (n = 112), with 50% of them higher than 200 μg/kg and 93% higher than 100 μg/kg, suggesting a need to consider the still uncertain health risks from rice iAs exposure for residents in the MRD as discussed in the following section.

4.5.4 Uncertainties in Health Risk Assessment of iAs Exposure from Rice

Much uncertainty remains in the health risk assessment of rice iAs exposure. Accurate exposure assessment for a population is challenging due to highly heterogenous iAs levels in rice grains and a diverse range of dietary intake of rice. Further, both the

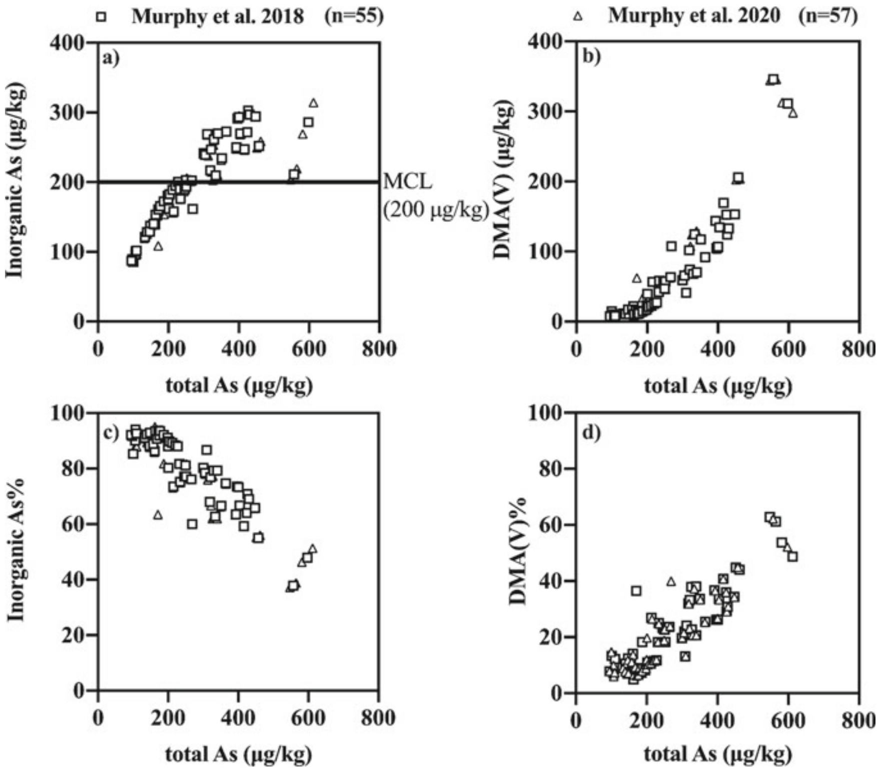


Fig. 4.9 Arsenic speciation in rice grains (n = 112) of Cambodia. Concentrations of iAs (**a**) and DMA(V) (**b**), and the percentages of iAs (**c**) and DMA(V) (**d**) are plotted versus the tAs. Data shown in squares and triangles are from Murphy et al. (2018) and (2020), respectively, and are from Preak Russey, Kandal Province of Cambodia. Rice grains also contain organoarsenicals DMA(V) and MMA(V), with DMA(V) dominant and accounting for >90% of methylated As. The positive correlation between %iAs and the tAs ($R^2 = 0.7906$) and the negative correlation between %methylated As and tAs ($R^2 = 0.7755$) are both significant (Pearson, $p < 0.0001$). The Maximum Contaminant Level (MCL) for iAs in rice grain of 200 mg/kg recommended by the WHO, FAO, and the EU is shown as a thick line in **a** (FAO/WHO, 2014)

bioavailability and the toxicity of iAs in rice, once ingested by humans, have seen very few in vivo investigations. These uncertainties are described first before an assessment of health risks of iAs exposure from rice in the lower MRD is made based on existing iAs data in rice and established food consumption patterns in Sect. 4.5.5.

Uncertainties in As Speciation Assumption and Variabilities in Rice Intake

Measurements of iAs levels in rice grains are still too few at present despite the heterogeneity of iAs levels observed in rice (see Sect. 4.5.3). For this reason, most exposure assessment until now simply assumes 100% iAs levels in rice (EFSA, 2014), resulting in an overestimation of rice iAs exposure, especially for rice with >200 µg/

Table 4.10 %iAs in rice grain of Cambodia adopted based on %iAs versus tAs (Fig. 4.9c)

n = 112	%iAs in rice grain of Cambodia		
tAs range (μg/kg)	<200	200–400	>400
tAs Average ± SD (μg/kg)	149 ± 32	292 ± 61	473 ± 70
%iAs Average ± SD	90 ± 5	77 ± 8	58 ± 11

kg tAs (Table 4.10). Although rice As speciation data have only been reported in two studies in Cambodia, they nevertheless cover a wide range of tAs concentrations (Fig. 4.9). We take advantage of the dependence of %iAs on tAs concentrations in Cambodian rice grains (Fig. 4.9c) and adopt the mean values of %iAs for three categories of tAs levels to accommodate the decrease of %iAs as tAs increases (Table 4.10). While this approach is not as accurate as an actual measurement of rice iAs, it is based on MRD rice speciation data and reflects the dependence of %iAs on tAs in global rice grain data (Zhao et al., 2013a, 2013b).

Rice consumption varies globally by nearly four orders of magnitude (0.9–650 g/person/day) among countries according to UN FAO 2004 data (Meharg & Zhao, 2012). Rice is a major staple in Southeast Asian countries (>300 g/person/day) but is only occasionally consumed in European and African countries (<50 g/person/day). Rice consumption also varies in any given country among different ethnic groups (EFSA, 2014). To the best of our knowledge, studies have not collected rice consumption and rice As speciation data simultaneously in the MRD. Therefore, the variations in rice intake among individuals are not considered in exposure assessment. According to World Rice Statistics—FAOSTAT, Cambodian's per capita milled rice consumption was 430 g/person/day in dry weight in 2019. With a more developed economy, the Vietnamese consumed less rice on average (376 g/person/day, dry weight) with a decreasing trend year by year (*FAOSTAT*). These values are adopted for our estimations of rice iAs intake described later.

Two examples are given here to illustrate that integrating measurements of As speciation with probabilistic models can establish a more accurate assessment of iAs exposure from food intake (Xue et al., 2010; Zhou et al., 2020). Coupled with ingestion rates and body weights from the National Health and Nutrition Examination Survey (NHANES) from 2003 to 2004 in the US, Xue et al. (2010) used the Stochastic Human Exposure and Dose Simulation-Dietary model to estimate dietary iAs exposure. The results indicate that the mean daily iAs exposure from food (n = 16,931) is 0.05 ± 0.09 μg/kg/day (5th–95th: 0.01–1.4 μg/kg/day), which is around two times higher than iAs from water exposure (0.025 ± 0.104 μg/kg/day, n = 16,883). Among all the foods, rice iAs exposure (0.0085 ± 0.0153) μg/kg/day contributes to 17% and ranked the third, while the largest portion is from vegetables (24%) and the second largest is from fruit juices and fruits (18%). Zhou et al. (2020) conducted a dietary survey (n = 1873) of an urban population in China and analysed 480 market rice samples for tAs and As speciation. Via Monte Carlo simulation, the mean estimated average daily dose of rice iAs exposure is 0.18 μg/kg/day (5th–95th: 0.001–1.224 μg/kg/day), approximately twenty-one times higher than that of the US population. Both studies highlight the variability of dietary and rice iAs intake in a single country.

Uncertainties Introduced by Cooking Water As and Cooking Practice

Unlike South Asians who have a preference for cooking parboiled rice (boiling and drying raw rice before dehusking, often cooked with excess water with the gruel discarded in the end), East and Southeast Asians usually prefer non-parboiled rice cooked with limited water. Regardless of how the rice is processed or cooked, cooking water introduces uncertainty for rice As risk assessment. Although only a few studies have assessed cooked rice tAs level and As speciation, the observations suggest that using high-As water to cook rice enhances tAs and iAs levels in cooked rice. For example, concentrations of iAs in cooked rice (n = 4) increased from 318 ± 84 to 2,255 ± 610 μg/kg, corresponding to cooking water with 0 or 500 μg/L As(V) in a lab experiment (Laparra et al., 2005). In areas with As-contaminated groundwater in Bangladesh, researchers asked two locals to cook market rice (173 μg/kg) with their tube well water (372 or 223 μg/L). Correspondingly, the tAs contents in wet cooked rice increased to 360 ± 16 and 256 ± 40 μg/kg (Bae et al., 2002). A subsequent study in southwestern Bangladesh found that tAs in two parboiled rice and two non-parboiled rice increased by 3 to −58% respectively after cooking with a limited amount of groundwater containing 130 μg As/L without discarding the gruel (Rahman et al., 2006).

Cooking with excess quantities of low-As water followed by decanting the extra water or gruel appears to reduce tAs contents in cooked rice (Brammer, 2009). A laboratory experiment found that cooking with excess deionized water (6:1 water volume: rice volume) reduced tAs and iAs contents by 35 and 45% respectively in cooked rice, compared with raw rice (long-grain and basmati rice, bought from the UK, Indian origin) (Raab et al., 2009). Another lab study found that cooking market rice purchased in Maryland, USA with excess water (10:1 water weight: rice weight) reduced iAs contents in polished long grain rice, parboiled rice and brown rice by 40, 60 and 50% respectively (Gray et al., 2016). Unfortunately, micronutrients in rice such as iron, folate, niacin and thiamin were also lowered by 50–70% at the same time. When low-As water is used to cook rice by rural Bengali households, tAs contents in 29 cooked rice (189 ± 6 μg/kg) were lower than those of raw rice (283 ± 13 μg/kg), with average iAs levels also lowered from 194 ± 8 to 123 ± 8 μg/kg (Halder et al., 2014). In West Bengal, a study reported that the level of tAs in rice (n = 55) cooked with water with non-detectable (<3 μg As/L) ranged from 33 to 138 μg/kg (Mean: 65 μg/kg, wet weight), though it is difficult to compare with the tAs concentrations in raw rice that ranged from 138–482 μg/kg (Mean: 249 μg/kg, wet weight) due to different water contents (Pal et al., 2009).

In the MRD, similar effects of enhancement of As in cooked rice by cooking water have been reported by O'Neil et al. (2013) for Prey Veng Province, Cambodia (Table 4.9). However, in Kandal, Kratie and Kampong Cham of Cambodia, no significant changes in tAs contents in rice after cooking were evident (Table 4.9) (Phan et al., 2013), although the As levels in cooking water were not measured. It is possible households from the study areas of Kandal, Kratie and Kampong did not use groundwater for cooking.

Uncertainties in Bioavailability and Toxicity of Rice iAs

Compared to water iAs, the bioavailability and toxicity of rice iAs are more difficult to demonstrate, with much remaining to be explored and understood. In the following section, results from several in vitro and in vivo studies are summarized to shed light on the bioavailability of rice iAs.

Several in vitro studies simulated gut enzymatic and chemical conditions, i.e. physiologically based extraction tests (PBET) to evaluate rice iAs bioaccessibility. Although in vitro studies are not illustrative of the actual absorption into organisms, the soluble fractions nevertheless can be considered as the upper limit of bioavailability, which can be used to corroborate with bioavailability results from in vivo studies (Ruby et al., 1996). Ackerman et al. (2005) demonstrated a mean of 88.9% (84–94%) of bioaccessibility of iAs in five US cooked rice samples with various ranges of DMA (22–270 μg/kg) and iAs (31–108 μg/kg) after in vitro extraction, suggesting similar bioaccessibility of iAs even though %iAs in rice can vary. Laparra et al. (2005) determined the bioaccessibility of eight types of rice (50–530 μg/kg tAs) cooked with different levels of As(V) (200, 400, 600, 700, 900, 1000 μg/L) in water as 63–99% (cooked rice iAs: 810–3730 μg/kg), suggesting the original rice iAs and additional dosed As(V) by cooking water were both highly soluble. Du et al. (2019) estimated the bioaccessibility of tAs in 42 rice samples (tAs: 50–230 μg/kg) from a mining site in Hunan, China by PBET. The average was 71.7 ± 13.5%, further demonstrating that the bioaccessibility of iAs is not dependent on tAs levels.

Although rice iAs bioaccessibility may not depend on tAs levels, nutrients have been shown to be an influencing factor. Alava et al. (2013) investigated the effect of extraction parameters on the bioaccessibility of iAs in rice, and found the bioaccessibility of As(V) was reduced from 80 to 68% with increasing levels of bile salt while fibre content had no significant effect on rice iAs bioaccessibility. Later, the same group (Alava et al., 2015) found that compared with Western diet (fat and protein rich), rice iAs bioaccessibility increased from 50 to 73% for Asian (fiber rich) diet, which could result from the fat and protein difference considering the minor effect of fibre contents.

A swine model was established to evaluate the bioavailability of As species in cooked rice, finding that 89% of iAs and 33% of methylated As are bioavailable (Juhasz et al., 2006). However, the majority of iAs in rice comes from iAs added to the cooking water, which may differ from the bioavailability of iAs native to rice grains.

According to the "Critical aspects of EPA's IRIS assessment of inorganic arsenic: Interim report" (NRC, 2013), there had been only one pilot in vivo study that assessed rice iAs bioavailability in humans (He & Zheng, 2010). The report further notes that there is a near absence of concrete data in the absorption and metabolism of rice iAs. Due to variabilities in %iAs in rice and rice intake described earlier, it remains very challenging to conduct an epidemiological study to quantify health risks from ingesting rice iAs. This is likely why regulators have treated the toxicity of rice iAs the same as that of water iAs, a reasonable assumption guided by the precautionary principle, and supported by two in vivo studies summarized below.

Two Asian female adults volunteered for a 10-day diet experiment with a 5-day diet consuming wheat plus selected low-As containing food items, followed by a 5-day diet replacing wheat with rice (He & Zheng, 2010). The rice consumed was purchased from a supermarket in New York City with a tAs concentration of 148 ± 4 μg/kg (n = 3), with %iAs of 78% and %DMA(V) of 19%. The average rice intake was 282 ± 86 g/day for one subject (V1), and 122 ± 34 g/day for another (V2). A mass balance approach (comparison between the urinary As excretion and the food As intake) found that the percentage of dietary arsenic intake excreted by urine was 58% for V1 and 69% for V2, respectively. Assuming that 33% of the DMA(V) in ingested rice was bioavailable to humans (Juhasz et al., 2006) and excreted without further metabolism, the bioavailability of iAs in rice was estimated to be 66% for V1 and 80% for V2, respectively. Because As, once ingested, is also distributed and accumulated in other parts of human body such as skin, internal organs, hair, and nails etc., this urinary excretion-based bioavailability assessment reflects an underestimation. After switching to the rice diet, the %DMA(V) in urine decreased from 83 to 77 ± 3% for V1 and from 92 ± 5 to 88 ± 9% for V2, with minor %MMA(V) and %iAs also detected in urine. Another study conducted a fixed rice intake experiment with six adult male European volunteers. After daily ingestion of 300 g of dry rice (iAs: 99 μg/kg; DMA(V): 99 μg/kg; MMA(V): 3 μg/kg; tAs: 274 ± 10 μg/kg) for three consecutive days, the mean urinary tAs of 6 subjects increased from 6.8 to 49.9 μg/L. By the 5th day, ~ 40% As from ingested rice since the 1st day of the experiment has been excreted by urine. This is slightly lower than the 58 and 69% values reported by the He and Zheng (2010) study because more As is expected to be excreted from the 6th day and so on. Similar to He and Zheng (2010), ~90% of urinary As was DMA(V) with the remaining ~10% being MMA(V) and iAs among 6 European subjects. These two studies provided unequivocal evidence that not only is rice iAs bioavailable, it is methylated in vivo, although whether the methylation occurs in human liver exclusively, or it may involve the human gut microbiome, remains debatable (Coryell et al., 2019).

4.5.5 *Exposure to Rice iAs and Health Risks in Cambodia and Vietnam*

Bearing the aforementioned uncertainties of rice As speciation, iAs toxicity and intake in mind, plus the complications of water iAs either directly via drinking water exposure route or as cooking water, the following assessment focuses solely on rice iAs exposure, though the water iAs exposure is summarized to underscore that only when water iAs exposure is non-existent then rice iAs exposure becomes important.

Hanh et al. (2011) assessed As intake from water and rice (n = 45) in Au Giang province, MRD of Vietnam, where groundwater As ranged from 0.1–977 μg/L (median 134 μg/L). Average daily consumption of water (3.7 and 2.7 L/day for male and female) and rice (300 and 250 g/day for male and female) were determined by interviews. Assuming 100% iAs in groundwater and 80% iAs in rice grains, per capita daily iAs intake from water was estimated to be 949 ± 714 μg/day for males and 607 ± 620 μg/day for females, while per person daily iAs intake from rice were 53 ± 18 μg/day for males and 45 ± 16 μg/day for females. Since 2008, residents in the area have switched drinking water source from groundwater to low-As filtered water or tap water. The daily iAs intake from water reduced significantly to 1.1 ± 1.7 μg/day for males and 1.8 ± 7 μg/day for females. This illustrates when water iAs intake is low, then the rice iAs becomes a major exposure route. Since 2008, the remaining and dominating iAs exposure is from rice, and were 0.91 ± 0.56 and 0.90 ± 0.57 μg/kg/day for males and females using the average body weights of 58 and 50 kg respectively. The European Food Safety Authority (EFSA) has recommended a $BMDL_{0.1}$ of 0.3 μg/kg/day, or a benchmark dose lower confidence limit value for 1% excess risk of cancers of the lung, skin and bladder, as well as skin lesions due to iAs (EFSA, 2009). Although the daily dose of iAs was significantly reduced after changing the water source, it still exceeded the $BMDL_{0.1}$, suggesting health risks posed by iAs intake from rice in lower MRD.

Rice iAs exposure was also evaluated in the MRD of Cambodia (Phan et al., 2013, 2014). In Prey Veng Province where groundwater As had been frequently detected, a survey evaluated iAs exposure from water and rice for 12 females and 11 males with body weights of 42.5 ± 11.1 and 55.4 ± 4.8 kg, respectively (Phan et al., 2014). The survey found that daily drinking water consumption was 1.375 ± 0.433 and 1.818 ± 0.337 L/day for females and males, and that the tAs concentrations of groundwater were 118 ± 139 μg/L. Thus, the daily iAs exposure from drinking groundwater was estimated to be 162 ± 2 μg/day for females and 215 ± 3 μg/day for males assuming 100% iAs in groundwater; or 3.818 ± 0.048 and 3.872 ± 0.046 μg/kg/day for females and males (Phan et al., 2014). The survey also determined that rice consumption was 450 ± 0 and 429 ± 72 g/day for males and females, and that the tAs concentrations of rice were 201 ± 50 μg/kg (Phan et al., 2014). Therefore, the daily iAs exposure from rice was 72.4 ± 0.2 μg/day for males and 69.0 ± 0.2 μg/day for females assuming 80% iAs in rice, or 1.306 ± 0.003 and 1.623 ± 0.006 μg/kg/day for males and females respectively (Phan et al., 2014). Like Vietnam, water iAs exposure exceeds rice iAs by several folds. But even when water As exposure is reduced through mitigation (see next section), iAs exposure from rice still exceeds the European $BMDL_{0.1}$. This is also the case for Kandal, Kratie and Kampong Cham Provinces where cooked rice tAs concentrations have been measured (Table 4.9) and used to estimate exposure. Phan et al. (2013) estimated rice iAs intake in Kandal, Kratie and Kampong Cham to be 1.8 ± 2.4, 0.6 ± 0.4 and 0.09 ± 0.07 μg/kg/day respectively, assuming a typical rice consumption of 450 g/person/day and an average body weight of 52 kg, as well as a mean of 80% of tAs as iAs. Again, rice iAs exposure in Kandal and Kratie have exceeded the European $BMDL_{0.1}$ but not in Kampong Cham.

Because it is imperative that water iAs exposure must be reduced, and that it is less difficult (though not easy) to address than rice iAs exposure, we illustrate the current scenario of the range and average rice iAs exposure excluding water iAs complications. Because rice grains in Cambodia display a wide range of tAs concentrations (Table 4.9), the daily intake of iAs from rice grains ranges from 3 to 174 μg/day (68 ± 106 μg/day) for Cambodian females and ranges from 4 to 219 μg/day (85 ± 133 μg/day) for Cambodian males. The estimate here uses three %iAs values corresponding to three ranges tAs levels (Table 4.10). The per person daily consumption rate of dry rice according to FAOSTAT in 2019 was 430 g/day in Cambodia. Because a survey (Sar et al., 2012) has found that men consume 26% more rice than women, so the male and female rice consumption is partitioned to be 381 and 479 g/day. Using an average body weight of 59.7 and 52.8 kg for male and female Cambodian respectively (WorldData, 2020), daily rice iAs exposure ranges from 0.06–3.67 μg/kg/day (mean 1.43 ± 2.23 μg/kg/day) for males, and ranges from 0.05–3.30 μg/kg/day (mean 1.28 ± 2.00 μg/kg/day) for females. Even if only the mean values are considered, they exceeded the European $BMDL_{0.1}$ by >4 fold. Given the similarities in tAs contents in raw rice grains (Table 4.9), daily rice consumption (376 g/person/day, FAOSTAT, 2019), and average body weight (61.2 kg male and 54.0 kg female Vietnamese, WorldData, 2020), the average of daily rice iAs exposure again shows a wide range from 30 to 133 μg/day (66 ± 33 μg/day) for Vietnamese males and from 25 to 111 μg/day (55 ± 28 μg/day) for Vietnamese females. This is equivalent to the daily iAs dose from rice grains ranging from 0.48 to 2.18 μg/kg/day with the average of 1.09 ± 0.54 μg/kg/day for males, or from 0.46 to 2.06 μg/kg/day with an average of 1.03 ± 0.51 μg/kg/day for females. The European $BMDL_{0.1}$ of 0.3 μg/kg/day is equivalent to 16.5 μg/day iAs intake for an adult of 55 kg weight, and is equivalent to drinking 2 L of water containing 8.25 μg/L iAs. In summary, the average daily exposure to iAs from rice alone in the MRD, at about 1.20 μg/kg/day for a 55-kg adult is equivalent to drinking 2 L of water containing ~33 μg/L of iAs.

4.6 Arsenic Mitigation and the Way Forward

Due to the latency effect of chronic inorganic arsenic exposure from drinking water, and that currently there is no cure other than reducing arsenic exposure, replacing drinking water supplies from wells with elevated arsenic in the Mekong River Delta with a low arsenic supply should be and has been the priority. Although there are no currently known plans to test all drinking water sources for arsenic in the Mekong River Delta regions for arsenic, our field work has discovered anecdotal evidence that many villages have switched to a communal water supply especially close to the capital city Phnom Penh of Cambodia. We recommend a Mekong River Delta drinking water quality survey to assess the remaining risks. This is the critical first step towards mitigating arsenic exposure from groundwater. The water quality survey whenever possible, should sample irrigation wells considering the substantial risks from rice exposure due to the usage of high arsenic groundwater for irrigation.

The assessment of rice iAs exposure in the MRD here, although still preliminary, is sufficient to underscore the need to pay attention to this hazard that is likely to become more threatening in the future after the water iAs exposure is brought under control. Due to the cumulative nature of As contamination of soil by irrigating with high-As groundwater, it is prudent to move away from irrigated agriculture practices using this unsafe groundwater source. Because surveys of paired paddy soil and rice sampling in the Mekong River Delta area are still uncommon, it is helpful to investigate arsenic cycling in the hydro-geo-biosphere to improve our knowledge of the bioavailability and toxicity of arsenic in rice. This will allow for a more reliable assessment of the at-risk areas and at-risk-rice cultivars. Such knowledge can inform plans to manage rice cultivation in the MRD that will increase rice productivity and ensure food safety.

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Chapter 5
Water Resource Availability and Use in Mainland Southeast Asia

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Abstract This chapter assesses water resource availability and use in the five countries in Mainland Southeast Asia (MSEA): Myanmar, Thailand, Laos, Cambodia, Vietnam. The total water resources in the region are estimated using a wide range of hydrometeorological data. Results show that the average annual runoff is about 1941.1 billion m^3 in the region. Regarding spatial differences, rainfall and runoff in the southern coastal areas are generally higher than the ones in the central and northern inland areas, and the western coastal areas have more rainfall than the eastern coastal areas. Moreover, results indicate that the overall utilization rate of water resources in the region reached 9%, mainly used for hydropower development, agricultural irrigation, fishery and aquaculture, shipping and other aspects. Agriculture was the primary water user (about 92.2%) in the study area compared to industrial (about 3.6%) and domestic (about 4.2%) water users. The region is divided into different water resource zones, including 7 first-level water resources zones, 17 s-level water resources zones, and 138 third-level water resources zones. The division is done by considering the hydrology conditions, natural landforms, administrative divisions, and river systems in the study area. Particularly, results show that the seven first-level water resources regions are all transboundary basins, implying that the water

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resources management in the region needs the solid cooperation and overall planning of all countries. Results show that the total water demand in MSEA will reach 200, 208, and 225 billion m^3 in 2025, 2030, and 2040, respectively. The prediction is obtained using the historical social and economic data. Social-economic developments are predicted to estimate the future water consumption. will assure a balance between the supply and demand of water resources in the study area, with asurplus of water resources supply ability.

5.1 Introduction

5.1.1 Study Area and Related Five Countries

Mainland Southeast Asia is located in the southeast corner of the Eurasian continent, surrounded by sea on its western, southern and eastern sides (Fig. 5.1). The five countries considered in this study are Myanmar, Thailand, Laos, Cambodia, and Vietnam, with a geographical location of 92°0′–109°30′ E and 5°30′–28°30′ N, covering a total area of about 1,938,700 km^2.

The elevation of the terrain of the region is low in the south and high in the north, with its north being closely connected with Southwest China. There are many mountains, rivers, and valleys in the area, for example, the Arakan Mountains in the west, the Hengduan Mountains in the middle, and the Truong Son Mountain ranges in the east. The highest mountain peak of above 5800 m in the study area is Mount Kaikabo in northwestern Myanmar (Dobby, 1959). Most of the rivers in this region flow from north to south, roughly in the same direction as the mountains. Famous rivers in the region are the Irrawaddy, the Salween, the Chao Phraya, the Mekong and the Red River (Fig. 5.2). The northern part of the study area has high mountains and deep valleys, and the terrain is mostly mountainous and hilly. Due to the rapid water flows, this region contains rich hydropower resources. In the southern region, the river valleys are open, the terrain is flat, and the water flow becomes slow. Consequently, sediment accumulates to form larger estuarine deltas and alluvial plains (Rigg, 2004).

Most of the region is located in the tropical monsoon climate zone which is not spatially homogeneous. It is under the joint influences of the Indian Summer Monsoon (ISM) and the Western North Pacific Monsoon (WNPM), which is significantly regulated by the El Niño Southern Oscillation (Chen et al., 2019; Räsänen et al., 2017; Wang et al., 2014). Most of the region has high temperatures throughout the year and is divided into dry and rainy seasons each year. The southwest monsoon prevails in the study area from May to October every year, and provides abundant precipitation (about 80% of the annual precipitation) to this region during the rainy season (Delgado et al., 2009, 2012; Yang et al., 2019). From November to May, the prevailing northeast monsoon causes dry weather and less rain in the dry season

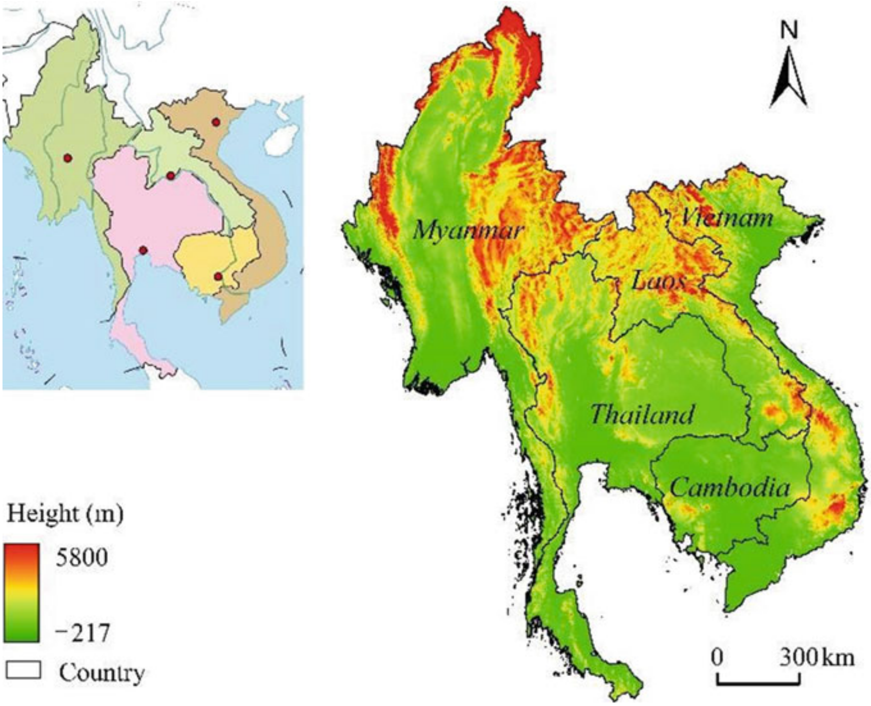

Fig. 5.1 Elevation and regional location of the study area of Mainland Southeast Asia (the red dot in the left-top figure shows the capital city of each country)

in most of the region (Nguyen-Le et al., 2015). The annual rainfall is about 500–5,400 mm, with an average magnitude of about 2183 mm, and the average annual temperature is −4–28 °C in the whole study area (Lutz et al., 2014).

The region has become one of the most dynamic and fastest economic regions globally (Rigg, 2004). In 2019, the population of the five countries reached 243 million, and the annual gross regional product (GDP) reached 926.9 billion USD. Among them, Vietnam has a population of 96.46 million, which is the most populous country in the region. Laos is the least populous country in the region, with only 7.17 million; Thailand has not only the largest GDP but also the largest GDP per capita. From 2000 to 2019, the GDP of the region increased fivefold, and the population increased by 18% (Table 5.1).

The economies of the region are in steady growth (Table 5.2). The GDP growth rates of Myanmar, Laos, Cambodia, and Vietnam are all above 6%. The study area's economy has developed rapidly, but at the same time, the problem of regional imbalances still exists. Myanmar and Cambodia's per capita GDP is less than US$ 2,000, while Vietnam and Laos are also in the ranks of lower-middle-income countries (Kumagai, 2015; MRC, 2011).

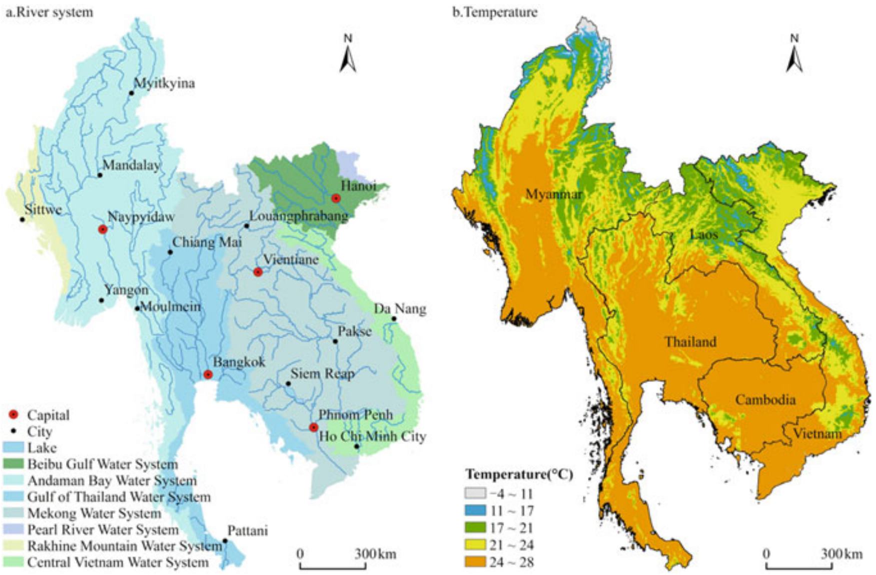

Fig. 5.2 River systems and the annual average temperature in the study area

Table 5.1 Population profile of the study area in 2019

Index	Myanmar	Thailand	Laos	Cambodia	Vietnam
Population/million	54.05	69.63	7.17	16.49	96.46
Rural population/million	37.37	34.33	4.61	12.56	61.13
Urban population/million	16.67	35.29	2.56	3.92	35.33
Rural population/% of total population	69	49	64	76	63
Urban population/% of total population	31	51	36	24	37
Population growth/%	0.63	0.28	1.52	1.45	0.96
Rural population growth/%	0.23	−1.21	0.53	0.9	−0.15
Urban population growth/%	1.51	1.76	3.33	3.21	2.91

Table 5.2 Social and economic overview of the study area in 2019

Index	Myanmar	Thailand	Laos	Cambodia	Vietnam
GDP/billion USD	76.1	543.6	18.2	27.1	261.9
GDP per capita/USD	1408	7808	2535	1643	2715
GDP growth/%	2.89	2.37	4.65	7.05	7.02
Agriculture, value added/% of GDP	23.93	8	15.29	20.71	13.96
Industry, value added/% of GDP	31.92	33.4	30.91	34.23	34.49
Services, value added/% of GDP	44.15	58.59	42.65	38.85	41.64

5.1.2 Data Used

In this chapter, the water resource and its use in the five countries (Myanmar, Thailand, Laos, Cambodia, and Vietnam) in the region are investigated. It is noted that the "blue" water (Mao & Liu, 2019) is mainly considered here while we do not consider "green" water resources in this study.

There is an uneven distribution of meteorological stations in the five countries, and there have also been different observation periods in these meteorological stations (Chen et al., 2018; Villafuerte & Matsumoto, 2015; Wang et al., 2016). Due to the scale of the analysis and data availability, different datasets may have different spatial resolutions, but we mainly focused on temporal aspects in the study. To ensure the water resources studies in the region, four datasets of precipitation and runoff were collected, and they were compared with the precipitation and runoff data from the Food and Agriculture Organization (FAO) of the United Nations (Ono et al., 2013; Sun et al., 2018; Yatagai et al., 2009, 2012). All the datasets have the same periods from 1981 to 2010. Three precipitation datasets were obtained from the Global Earth Observation for Integrated Water Resource Assessment (EartH2Observe), and the other one was from the Climatologies at high resolution for the earth's land surface areas (CHELSA).

For runoff data, three datasets from the Earth2Observe (Schellekens et al., 2017) and one dataset based on China's transboundary Water Resources estimation were selected (Yan et al., 2019). The four runoff datasets were developed by researchers at the European Centre for Medium-Range Weather Forecasts (ECMWF), Universiteit Utrecht in the Netherlands, Universitat Kassel in Germany, and at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. More details can be found in Table 5.3.

To this end, the hydrology conditions, natural landforms, administrative divisions, and water systems in the region are considered together to divide the whole study area into different water resource zones in Sect. 5.2. In Sect. 5.3, the total amount of water resources (including precipitation and runoff) in the region is estimated. In Sect. 5.4, the overall utilization of water resources in the region is investigated, by considering different water use indicators. In Sect. 5.5, historical social and economic data are used, and the social-economic developments are predicted to estimate the future water consumption (including agricultural and domestic water demands) in the region, and the future balance between the supply and demand of water resources in the study area in further investigated.

Table 5.3 Hydrometeorological data used for this study

Name	Spatial resolution	Period
Precipitation reanalysis data (Total Precipitation-Global-ECMWF)	0.25° × 0.25°	1979–2012
Precipitation reanalysis data (Total Precipitation-Global-Universiteit Utrecht)	0.25° × 0.25°	1980–2014
Precipitation reanalysis data (Total Precipitation-Global-Universitat Kassel)	0.25° × 0.25°	1980–2014
Precipitation reanalysis data (Climatologies at high resolution for the earth's land surface areas)	0.0083° × 0.0083°	1979–2013
Runoff reanalysis data (Total Runoff-Global-ECMWF)	0.25° × 0.25°	1980–2014
Runoff reanalysis data (Total Runoff-Global-Universiteit Utrecht)	0.25° × 0.25°	1980–2014
Runoff reanalysis data (Total Runoff-Global-Universitat Kassel)	0.25° × 0.25°	1979–2012
Runoff reanalysis data (China's transboundary water resources estimation using machine learning approaches)	0.1° × 0.1°	1979–2000

5.2 Water Resource Zonation

To investigate the characteristics of water resources in various areas of MSEA, the whole region is divided into different water resource zones. The water resource zonation in the study area is carried out based on the administrative divisions, hydrometeorology conditions, natural landforms, and river systems of the region, referring to the relevant principles of China's water resources zoning, and also combining the existing water resources development and utilization plans in the study (Xi et al., 2016; Zuo et al., 2018). To be specific, the hydrological and meteorological data were collected, based on the river-basin maps (Lehner & Grill, 2013), topographic maps, and administrative division maps of the region (GADM, https://gadm.org/download_country_v3.html/). The physical geography, human history and political environments of the study area were comprehensively considered to construct the water resource zones in the region (Chaowiwat et al., 2019; Eastham et al., 2008; Inomata & Fukami, 2008; Kravtsova et al., 2009; Lin et al., 2019; Minderhoud et al., 2019; Molle & Hoanh, 2011; Than & Maung, 2017). The division of water resource zones in this study area is different from the typical small and medium-scale divisions. It is necessary to consider the characteristics of the river basins and consider the political influence of transnational river basins.

Using the GIS-based method of watershed topography, the water resource zones of the whole region are divided into three levels, with mountainous areas and plains as zoning indicators. The specific division approaches and steps are explained as follows:

First-level water resource zones: There are differences in water resources, hydrometeorology, topography, and socio-economic conditions in different geographic areas.

Existing large and medium-scale studies mainly used geographic areas as the basic water resource unit, and the basin areas of major rivers in the region are large. Therefore, the division of the first-level water resource zones mainly adopts the method of combining the geographical areas and the division of the river basin systems.

Second-level water resource zones: The river system map of the region and the first-level zoning map of water resources were overlaid in ArcGIS 10.2 software, and the second-level water resource zones were delimited in each first-level area. For the secondary districts with complex water systems or obvious differences in water resources, the independence and integrity of their water systems should be ensured, and the regionalization should mainly refer to the basin distribution, while considering the connection with the existing water resources regionalization results.

Third-level water resource zones: Based on literature for the quantitative definition of the spatial scope of mountains in China and the achievements of China Digital Mountain Map (Nan et al., 2016; Zhang et al., 2013), three indexes of altitude, slope and degree of fluctuation were selected to establish the quantitative definition index of mountains. Finally, it was divided into third-level water resource zones with mountainous areas and plains as basic units.

According to the above mentioned principles and methods, water resource zoning results in the region were obtained. According to different needs, the whole region was divided into first-level water resource zones, second-level water resource zones (Fig. 5.3), and third-level water resource zones (Fig. 5.4). There are 7 first-level water resource zones in the region, namely: Rakhine Mountain Water System, Andaman Bay Water System, Gulf of Thailand Water System, Mekong Water System, Beibu Gulf Water System, Central Vietnam Water System, and Pearl River Water System. There are 17 s-level water resource zones, namely: Rakhine Mountain River System, Irrawaddy River, Chindwin River, Sitang River, Salween River, Southern Andaman Gulf, Southwestern Gulf of Thailand, Chao Phraya River, Southeastern Gulf of Thailand River, Mekong Delta, Lower Mekong River, Middle Mekong River, Upper Mekong River, Red River, Ma River, Central Vietnam Water System, Zuojiang River. There is a total of 138 third-level water resource zones (Fig. 5.4). In alphabetical order, the 7 first-level water resource zones contain 6, 50, 25, 33, 9, 14 and 1 third-level water resource zones respectively. The specific division is shown in Table 5.4.

5.3 Water Resources Estimation

5.3.1 Precipitation and Runoff

By comparing with the average annual precipitation data released by FAO, the appropriate precipitation data sources for each country were selected, with the same periods from 1981 to 2010. Specifically, the CHELSA data was used in Myanmar, the Universität Kassel data was used in Thailand, the Universiteit Utrecht data was used in

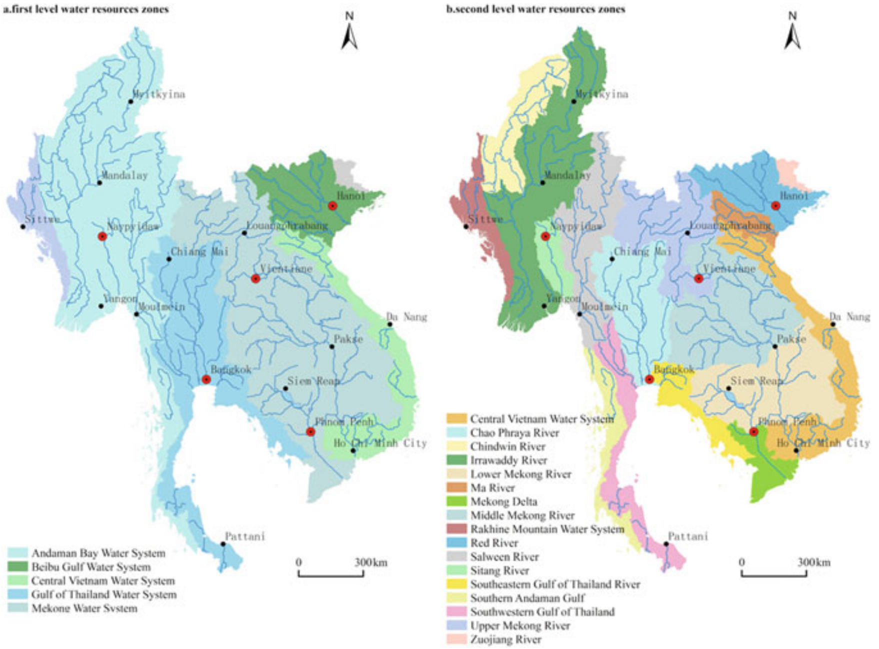

Fig. 5.3 Schematic diagram of first- and second-level water resource zones in the study area

Vietnam and Cambodia, and the ECMWF data was used in Laos (Karger et al., 2017; Schellekens et al., 2017).

The Pearson-III (P-III) probabilistic distribution was used for the hydrological frequency analysis here, as a basis of estimating the statistical characteristics (mean value, coefficient of variation (C_v), coefficient of skewness (C_s)) of the annual precipitation in each country. After that, the annual precipitation design values in each country under guarantee rates of 20, 50, 75, and 95%, respectively, were obtained. The annual precipitation design values of the five countries are shown in Table 5.5.

The annual average rainfall has a value range of 1500–2100 mm in the region. The rainfall in the summer and autumn seasons (May to October) is 1423 mm, accounting for 77% of the annual rainfall; the rainfall in winter and spring (November to May) accounts for 23% of the annual rainfall. Myanmar has the largest annual average rainfall, with an annual value of 2071 mm; Thailand has the smallest annual average rainfall, with an annual value of 1574 mm. Specifically, the rainiest months in Myanmar are from June to August, accounting for 58% of annual precipitation. The rainy months of precipitation in Thailand, Laos, Cambodia and Vietnam are concentrated from July to September, accounting for 39–47% of annual precipitation (Fig. 5.5).

The four runoff datasets released by FAO were used to find the most suitable runoff data for each country in the region. To be specific, the runoff data from the Universiteit Utrecht was used in Myanmar and Vietnam, the runoff data from the

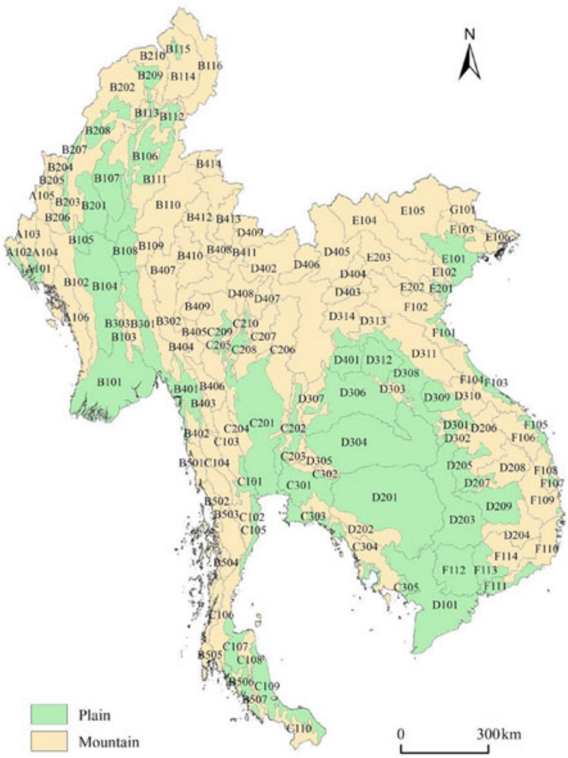

Fig. 5.4 Schematic diagram of third-level water resource zones in the study area

Universitat Kassel was used in Thailand and Laos, and the runoff data from ECMWF was used in Cambodia. The runoff depth in the study area was calculated here and it had a seasonal distribution throughout the year (Fig. 5.6). The runoff from June to October can account for 70% of the annual runoff, and the runoff from February to April is small, accounting for about 8% of the annual runoff.

It can be seen from Fig. 5.7 that the distribution pattern of rainfall and runoff depth in the study area is roughly the same in areas with low elevation but is different in areas with high elevation. The rainfall and runoff depth in the southern coastal area of the study area are generally higher than that in the central and northern areas. The western coastal area of the study area has more rainfall and more abundant water resources than the eastern coastal area. The annual rainfall in most regions is more than 1500 mm. The annual rainfall is above 3000 mm in the mountains of the Thanai River in northern Myanmar, the Rakhine coast in western Myanmar, the Irrawaddy Delta, the southeast coast of Myanmar, the west of the Malay Peninsula in Thailand, and the southwest coast of Cambodia. The annual runoff depth in these areas is more than 1500 mm, with the most abundant water resource quantity in the region.

Table 5.4 Results of second- and third-level water resource zones in Mainland Southeast Asia

Primary water resource zone	Second-level water resource zone	Distributed region	Third-level water resource zone
Rakhine Mountain Water System (A)	Rakhine Mountain Water System (A1)	Myanmar	6
Andaman Bay Water System (B)	Irrawaddy River (B1)	Myanmar	16
	Chindwin River (B2)	Myanmar	10
	Sitang River (B3)	Myanmar	3
	Salween River (B4)	Myanmar, Thailand	14
	Southern Andaman Gulf (B5)	Myanmar, Thailand	7
Gulf of Thailand Water System (C)	Southwestern Gulf of Thailand (C1)	Thailand	10
	Chao Phraya River (C2)	Thailand, Laos, Myanmar,	10
	Southeastern Gulf of Thailand River (C3)	Thailand, Cambodia	5
Mekong Water System (D)	Mekong Delta (D1)	Vietnam, Cambodia	1
	Lower Mekong River (D2)	Laos, Cambodia, Vietnam	9
	Middle Mekong River (D3)	Thailand, Laos,	14
	Upper Mekong River (D4)	Myanmar, Laos, Thailand	9
Beibu Gulf Water System (E)	Red River (E1)	Vietnam, Laos	6
	Ma River (E2)	Vietnam, Laos	3
Central Vietnam Water System (F)	Central Vietnam Water System (F1)	Vietnam	14
Pearl River Water System (G)	Zuojiang River (G1)	Vietnam	1

Table 5.5 Statistical characters (mean value, coefficient of variation (C_v), coefficient of skewness (C_s)) of annual precipitation and its design values in the study area

Country	Mean value given by FAO/mm	Mean value given by this data series/mm	C_v	C_s/C_v	Annual precipitation design values at different guarantee rates/mm			
					25%	50%	75%	95%
Myanmar	2091	2071	0.13	5.4	2231	2039	1876	1687
Thailand	1622	1574	0.07	2.6	1647	1571	1498	1399
Vietnam	1821	1834	0.07	3.0	1918	1829	1745	1631
Cambodia	1904	1897	0.06	4.5	1971	1892	1818	1719
Laos	1834	1858	0.1	2.1	1979	1851	1729	1564
MSEA	1872	1857	0.06	7.5	1926	1848	1778	1689

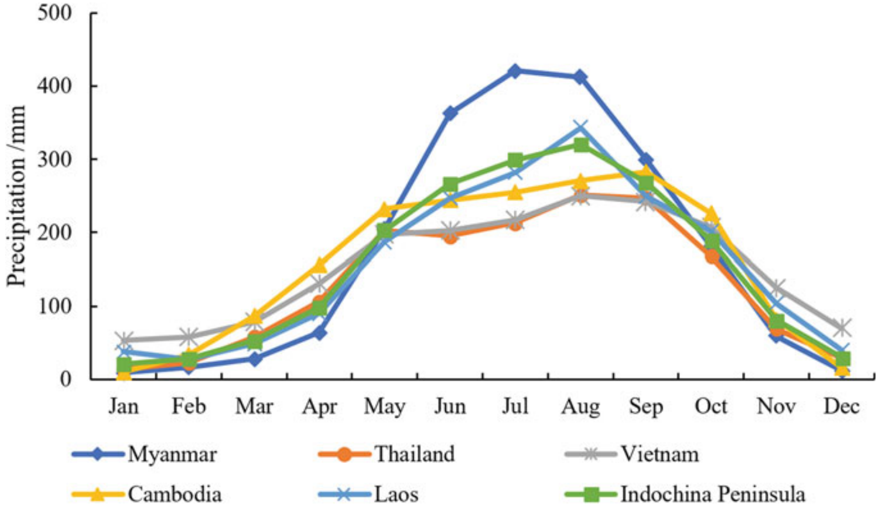

Fig. 5.5 Seasonal distribution of precipitation in the study area

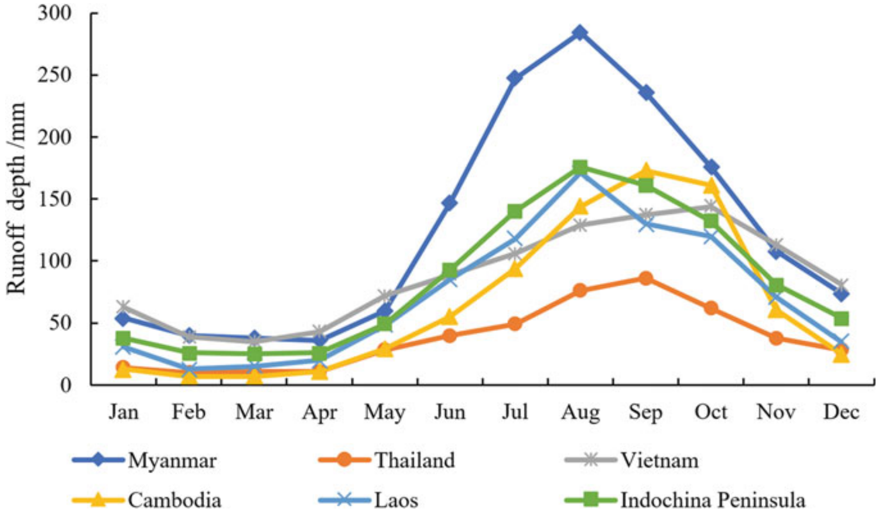

Fig. 5.6 Seasonal distribution of runoff depth in the study area

5.3.2 Water Resources

The Pearson-III (P-III) probabilistic distribution was used again for the runoff frequency analysis, as a basis for estimating the statistical characteristics (mean value, C_v, C_s) of the annual runoff in each country. The annual runoff design values in each country under different guarantee rates are shown in Table 5.6. The average

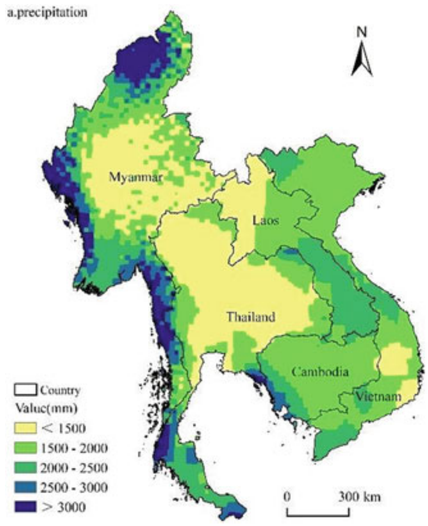

Fig. 5.7 Spatial distribution of **a** precipitation and **b** runoff depth in the study area

annual runoff in the region is 1941.1 billion m^3, and the amount of water resources can be seen to be relatively abundant. It can be seen from Table 5.6 that the country with the largest amount of water resources is Myanmar, which has an average annual runoff of 1,015 billion m^3; Thailand's annual average runoff is 232.6 billion m^3; Laos' annual average runoff is 203.3 billion m^3; Cambodia's annual average runoff is 141.5 billion m^3; Vietnam has an average annual runoff of 348.7 billion m^3.

The amount of water resources in each river basin was calculated based on the water resources division of the region (Table 5.7). Among the seven first-level water resource zones, the watershed with the largest amount of water resources is the Andaman Bay water system, with an average amount of annual water resources

Table 5.6 Statistical characters (mean value, coefficient of variation (C_v), coefficient of skewness (C_s)) of annual runoff and its design values in the study area

Country	Mean value of FAO series/10^9 m^3	Mean value of this data series/10^9 m^3	C_v	C_s/C_v	Annual runoff under different frequencies/10^9 m^3			
					25%	50%	75%	95%
Myanmar	1003.0	1015.0	0.11	1.91	1088.0	1011.0	937.7	838.2
Thailand	224.5	232.6	0.14	0.57	254.3	232.2	210.4	179.8
Vietnam	359.4	348.7	0.09	5.00	368.4	346.3	326.4	301.4
Cambodia	120.6	141.5	0.17	3.24	156.3	139.3	124.3	106.0
Laos	190.4	203.3	0.16	1.87	224.2	201.7	180.6	152.7
MSEA	1897.9	1941.0	0.07	0.71	2032.0	1939.9	1848.8	1719.5

Table 5.7 Water resources of the first-level water resource zones

Basin	Area/km^2	Annual precipitation/mm	Annual runoff depth/mm	Annual water resources/10^9 m^3
Rakhine Mountain Water System	55,544	2460	1474	81.9
Andaman Bay Water System	632,390	2287	1504	951.0
Gulf of Thailand Water System	308,146	1657	628	193.6
Mekong Water System	640,850	1689	674	432.0
Beibu Gulf Water System	128,698	1874	1059	136.3
Central Vietnam Water System	155,932	1812	852	132.9
Pearl River Water System	11,711	1581	742	87

of 951 billion m^3, followed by the Mekong River system, with an average amount of annual water resources of 432 billion m^3. The Pearl River system has the least amount of water resources, with an average annual amount of only 8.7 billion m^3. Furthermore, our estimated water resources in this study show a strong agreement with the FAO dataset.

5.4 Water Utilization

The development and utilization of water resources in each country in the region were studied. The data on water use released by FAO, the World Bank, the Statistical Yearbook of various countries and the National Bureau of Statistics of China in recent years were collected for this study. Based on these data, the historical water use data for the five countries were estimated. The current situation of water resource utilization in the region was investigated, including the total amount and proportion of agricultural water, industrial water and domestic water.

5.4.1 Water Use Analysis

The region is densely covered with water systems, with the Irrawaddy River, Salween River, Chao Phraya River, Mekong River and Red River distributed in the territory, and water resources are therefore rich. Based on the FAO data, during the baseline year of 2005, the per capita water resources of Myanmar, Cambodia and Laos were higher than the world average of around 9000 m^3 per capita. The per capita water resources of Thailand and Vietnam were about half of the world average; the water resources utilization rate in the region ranged from 2 to 26% and varies greatly (Hasson et al., 2013; Räsänen et al., 2017). In general, the utilization rate of water resources in Myanmar, Laos and Cambodia is relatively low, only between 2 and 3%. The utilization rate of water resources in Thailand and Vietnam exceeded 26 and 23% respectively. On the whole, the utilization of water resources in the region reached 9%. Due to the differences in the economic development levels, natural geographical conditions and political environment of these countries, the extent of and approaches to the utilization of rivers within these countries are different. In general, the water resources in the five countries of the region are mainly used for hydropower development, agricultural irrigation, fisheries, and shipping (Ziv et al., 2012).

5.4.2 Water Supply

As shown in Fig. 5.8, agriculture is the main water user in the region, and the proportion of industrial and domestic water is relatively small. Based on the FAO data, during the baseline year of 2005, the total amount of water resources utilized in the region is 178.00 billion m^3, of which industrial water accounts for 3.58%, agricultural water utilization is 92.21%, and domestic water utilizes only 4.21%. The total utilization of water resources in Myanmar is 33.00 billion m^3, of which industrial accounts for 1%; agricultural water utilizes about 89%, and the share of domestic water is about 10%. The total utilization of water resources in Thailand is 57.31 billion m^3, of which industrial water and domestic water account for a similar percentage (4.8%). Agricultural water utilizes the maximum amount of water resources with almost 90.4%. The total utilization of water resources in Cambodia is 2.18 billion m^3, of which industrial water accounts for only 1.5%; agricultural water utilizes 94.0%; and domestic water consumes 4.5%. The total utilization of water resources in Laos is 3.49 billion m^3, of which industrial water and domestic water consume only 4.9 and 3.7%, respectively. The agricultural water utilizes maximum water resources with 91.4% of the total usage. The total utilization of water resources in Vietnam is 81.86 billion m^3, of which industrial water shares 3.7%, agricultural water accounts for 94.8%, and domestic water is only 1.5%.

5.4.3 Major Water Use Indicators

It can be seen from Table 5.8 that the per capita comprehensive water consumption of Myanmar, Thailand and Vietnam exceeds 700 m^3; the per capita comprehensive water consumption of Laos is about 607 m^3, which is higher than China's per capita water consumption of 432 m^3 in 2005; while the per capita water consumption

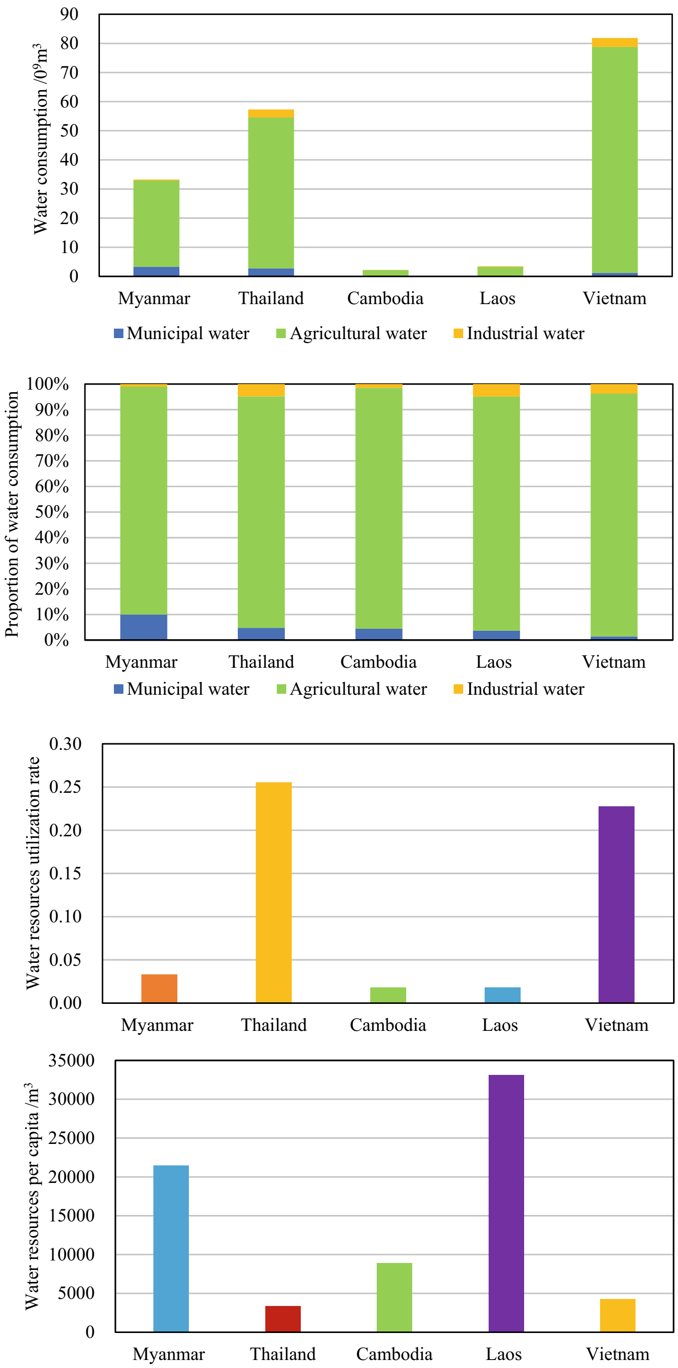

Fig. 5.8 Water utilization in the baseline year of 2005 in the study area

Table 5.8 Water consumption index in baseline year in study area

Country	Domestic water per capita/L day^{-1}	Comprehensive water consumption per capita/m^3	Irrigation water per acre/m^3	Industrial water for thousand USD/m^3	Water consumption per thousand USD GDP/m^3
Myanmar	195	711	935	385	2769.2
Thailand	113	866	683	26.7	302.8
Cambodia	20	162	432	17.3	346.7
Laos	62	607	784	265.7	1293.7
Vietnam	39	976	1128	139.6	1421.2

of Cambodia is only 162 m^3. In terms of per capita domestic water consumption, Vietnam, Cambodia and Laos consume less water, while the per capita domestic water consumption of Myanmar and Thailand exceed 100 m^3. In terms of irrigation water indicators, with the exception of Cambodia, the average irrigation water in other countries is above 40 m^3/acre. The industrial water consumption of Thailand and Cambodia is less than 100 m^3 per thousand USD, while the other three countries use more than 100 m^3 per thousand USD. From the perspective of GDP water consumption indicators of thousand USD, Thailand uses the least water consumption of 302.8 m^3, followed by Cambodia's 346.7 m^3. The other three countries all consume more than 1,200 m^3 of water. Among them, Myanmar has the largest water consumption of 2769.2 m^3. According to the GDP of thousand USD by water use indicators, Thailand has the highest water use efficiency among the five countries during the baseline year, while Myanmar has the lowest.

5.5 Water Demand Prediction

At present, there is a lack of studies on future water demand in the region, which is also a difficult issue (Alcamo et al., 2003, 2007; Hejazi et al., 2013; Rosegrant & Cai, 2002). For example, the simulation results of domestic, agricultural and industrial water demand based on the global hydrological model LPJML, provided by the ISIMIP2B project, were far lower than the current actual water consumption levels in these countries (Pokhrel et al., 2021). Therefore, we re-estimate the future water demand for the region adopting a different approach with the aim to obtain higher accuracy. The future water demand of the region was predicted by taking the five countries as water supply and water demand calculation units. By collecting the social and economic data of the study area, the social and economic development of the five countries from 2025 to 2040 is predicted, including the prediction of population and GDP and other social and economic indicators. On this basis, the water demand situation of each industry in the future is predicted, the predicted annual available water supply was calculated, and the balance between supply and demand of water resources was analyzed.

5.5.1 Social Development Prediction

The social development prediction is mainly aimed at predicting the future population and social economy. The population prediction is based on the World Bank data from 1990 to 2019, with 2019 as the baseline year, and the Malthusian model is used to predict the population from 2020 to 2040. The prediction model was generated using 70% of the data set (from 1991 to 2015) as training and the remaining 30% (from 2016 to 2019) as test data. Three groups of 1991–2015 (25 samples), 2001–2015 (15 samples), and 2006–2015 (10 samples) were selected respectively. The population data in different periods were fitted to the Malthusian prediction model (Prentiss et al., 2018) of the countries' total population in the region. The average relative error between the models was compared, and the optimal sequence were selected. After comparative analysis, it was determined that Myanmar, Thailand, Cambodia, and Vietnam used the average population growth rate data on a 10-year time scale, whilst Laos used the average population growth rate data on a 15-year time scale (see Table 5.9).

Comparing the population prediction results obtained by using the Malthusian method with the population prediction data released by the United Nations World Population Outlook WPP2019, the model here showed a more reasonable range of goodness-of-fit. The prediction results are shown in Table 5.10. It is predicted that the total population of the five countries in the region will reach 260.65 million in 2030, and 271.88 million in 2040.

The GDP prediction is based on data from 1990 to 2019, with 2019 as the baseline year, using the SPSS25 software to establish a time series prediction model for the five countries' GDP and each industrial structure. The prediction results are shown in Table 5.11. It is predicted that the total GDP of the five countries in the region in 2030 will reach US$1386.06 billion, and the total GDP in 2040 will reach US$1789.29 billion. The per capita GDP is expected to rise from US$3802 in 2019 to US$6581 in 2040.

Table 5.9 Malthusian prediction model of the total population of Mainland Southeast Asia

Country	Model	Data series	Number of samples	Malthusian prediction model
Myanmar	III	2010–2019	10	$P(t) = 5404.54e^{0.007t}$
Thailand	III	2010–2019	10	$P(t) = 6962.56e^{0.004t}$
Cambodia	III	2010–2019	10	$P(t) = 1648.65e^{0.016t}$
Laos	II	2005–2019	15	$P(t) = 716.95e^{0.016t}$
Vietnam	III	2010–2019	10	$P(t) = 9646.21e^{0.010t}$

Table 5.10 Prediction results of population and urbanization rate in the study area

Country	Total population/million				Urbanization rate/%			
	2019	2025	2030	2040	2019	2025	2030	2040
Myanmar	54.05	56.22	57.80	60.25	31	32	33	35
Thailand	69.63	70.55	70.85	70.67	51	57	62	71
Cambodia	16.49	17.87	18.95	21.10	24	26	29	33
Laos	7.17	7.79	8.27	9.20	37	40	43	50
Vietnam	96.46	101.32	104.78	110.67	37	41	45	53
MSEA	243.79	253.75	260.65	271.88	38	42	46	52

Table 5.11 Economic prediction results of the study area

Country	GDP/billion USD				GDP per capita/USD		
	2019	2025	2030	2040	2025	2030	2040
Myanmar	76.09	97.3	114.98	150.34	1731	1989	2495
Thailand	543.65	653.88	732.96	891.0	9269	10,346	12,608
Cambodia	27.09	41.7	53.88	78.25	2334	2844	3709
Laos	18.17	21.36	23.97	29.19	2743	2898	3172
Vietnam	261.92	370.16	460.27	640.51	3653	4393	5788
MSEA	926.92	1184.4	1386.06	1789.29	4668	5318	6581

5.5.2 Agricultural Water Demand Prediction

The main water demand is agricultural irrigation. According to relevant domestic and foreign norms and standards, the irrigation water quota per area unit of cultivated land can be calculated under the guarantee rate of 50, 75, and 95%. The total amount of irrigation water is directly proportional to the amount of irrigated cultivated land. The agricultural irrigation water on a certain area of arable land can be determined by the following formula:

$$W_n = S_N \times D_N \tag{5.1}$$

where W_n represents the total amount of irrigation water in year t; S_N is the area of arable land in year t; D_N is the irrigation water consumption per unit area.

Figure 5.9 shows the prediction of the future irrigation area in the study area. In recent years, the agricultural production in the study area has gradually developed, and the planting of crops has increased. Based on the development of various crops in recent years and the agricultural development plan of the study area, combined with the irrigated area data of the inter-departmental impact model comparison project ISIMIP, the irrigated area of the five countries in the region is predicted. The irrigation water index is an important factor in the prediction of agricultural water demand.

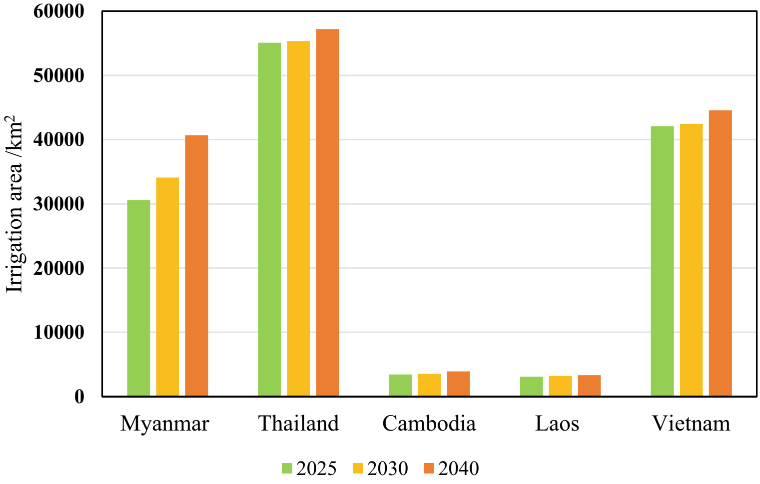

Fig. 5.9 Prediction of irrigation area in the study area

According to the future economic development of these countries, referring to the water quota and water resource bulletin of the same economic development level, the prediction level of the annual irrigation water index in the study area is predicted.

According to the prediction results of irrigation area and water consumption, the annual water demand is predicted using the quota method. The total agricultural water demand in the region will reach 180.8 billion m^3 in 2025, 1865 billion m^3 in 2030 and 2004 billion m^3 in 2040 (see Fig. 5.10 and Table 5.12).

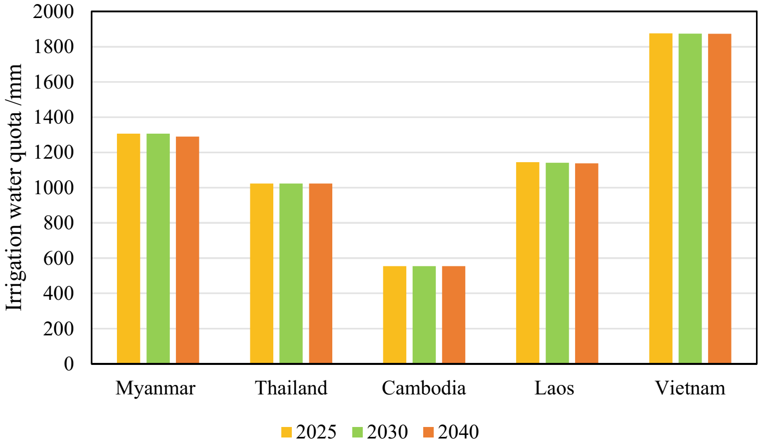

Fig. 5.10 Prediction of irrigation water quota in the study area

Table 5.12 Prediction results of agricultural water demand in the study area/10^9 m^3

Country	2025	2030	2040
Myanmar	39.95	44.54	52.43
Thailand	56.42	56.68	58.57
Cambodia	1.9	1.97	2.17
Laos	3.54	3.66	3.79
Vietnam	79.02	79.65	83.47

5.5.3 Domestic Water Demand Prediction

Residential water demand is divided into urban water demand and rural water demand. The calculation indexes include population, urbanization rate, and water consumption quota. Natural population growth and changes in water quotas are the principal indicators that affect domestic water consumption. Referring to the research reports and regulations of relevant regions at home and abroad, the future domestic water quota was determined. Considering the future economic development status and water-saving technology level of various countries, it was assumed that there will be no major changes in the daily water consumption per capita in cities and rural areas in each country, and the urbanization rate of the region will keep increasing in the future. Therefore, the prediction results of the water quota index indicate that for the countries of the region from 2025 to 2040, the residential water quota will keep increasing in the future, which is similar to the trend of the continuous development of the total population of various countries, and the total increase in residential water consumption indicators will be relatively small (Table 5.13).

Based on the population prediction data and the results of water quota indicators, the quota method can predict the domestic water demand in the future. The total domestic water demand in the region is expected to be 8.66 billion m^3 in 2025 and 9.07 billion m^3 in 2030. The specific prediction results are shown in Table 5.14.

Table 5.13 Prediction results of residential water quota in the study area/L day^{-1}

Country	2025			2030			2040		
	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total
Myanmar	118	70	85	118	70	86	118	70	87
Thailand	136	73	109	136	73	112	136	73	117
Cambodia	119	53	70	119	53	72	119	53	75
Laos	127	59	86	127	59	88	127	59	93
Vietnam	120	73	92	120	73	94	120	73	98

Table 5.14 Prediction results of domestic water demand in the study area/10^9 m^3

Country	2025			2030			2040		
	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total
Myanmar	0.78	0.97	1.75	0.83	0.99	1.82	0.92	0.99	1.91
Thailand	1.98	0.81	2.79	2.16	0.73	28.9	2.47	0.56	3.03
Cambodia	0.2	0.25	0.45	0.24	0.26	0.5	0.31	0.27	0.58
Laos	0.14	0.1	0.24	0.16	0.1	0.27	0.21	0.1	0.31
Vietnam	1.82	1.59	3.41	2.06	1.54	3.6	2.55	1.4	3.95

5.5.4 Water Resources Balance and Open Issues

The total water demand of the region in 2025, 2030, and 2040 is obtained by predicting water demand for life, agriculture and industry (Fig. 5.11). Among them, the total water demand in 2025 is estimated to be 20.27 billion m^3, 208.03 billion m^3 in 2030, and 225.83 billion m^3 in 2040. In general, the water demand in the region indicates an upward trend. Among them, Myanmar and Vietnam will have larger water demand growth, while Cambodia, Laos, and Thailand will have relatively small water demand growth in the future.

In summary, a water demand prediction model was established based on the combination of socio-economic development trends and historical water consumption data of various industries, and the social water consumption in future scenarios was estimated. The current water supply and water conservancy project planning for the water supply prediction was further investigated. Finally, the relationship between water demand and water supply was analyzed. The results of the balance of supply and demand are shown in Table 5.15. The amount of water supply shows that Myanmar will have the maximum water surplus in 2025, 2030, and 2040 with 19.42, 22.82, and 14.8 billion m^3, respectively. In contrast, Cambodia will have the minimum water surplus in 2025, 2030, and 2040 with 0.94, 1.23, and 0.63 billion m^3, respectively. Vietnam, Laos, and Thailand will also have a reasonable amount of water surplus (within a range) to 2040.

Considering that climate will likely change in the region significantly (Supari et al., 2020; Tangang et al., 2020; Weiss, 2009), the effective surplus of water supply will play a significant role in the future water supply in the region. It is projected that the annual mean temperature in the region will increase between 1.5 and 3.3 °C (SSP2-4.5; medium emissions scenario) by 2100 (Almazroui et al., 2020; Gutiérrez et al., 2021). Accordingly, the annual mean precipitation is also expected to increase under all scenarios (Almazroui et al., 2020). The drier season is projected to have more impact on Vietnam and Thailand (Weiss, 2009). This will eventually increase the water stress and influence water supply in some parts of the region, especially in Thailand and Vietnam. In addition, the projection of the models indicates an increase in the number of extreme precipitations in the future, while the total amount of precipitation will be reduced (Lorenzo & Kinzig, 2020; Supharatid et al., 2021).

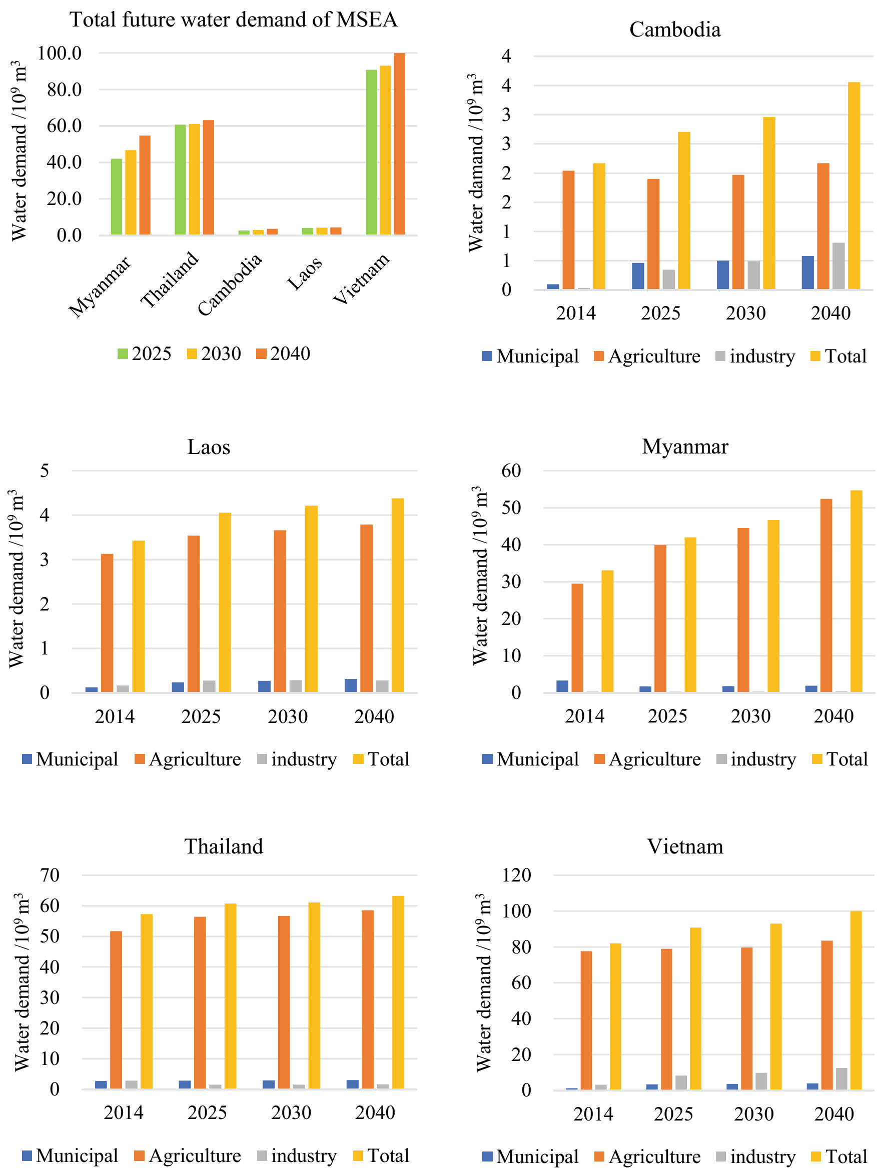

Fig. 5.11 Prediction results of total water demand in the study area

Hence, this region may face more drought events and flood disasters in the future. In this context, Cambodia, Laos and Thailand will be more at risk due to lower water surplus in future. Taking full advantage of the existing water supply facilities and considering future water conservancy projects, the water resources in the region can

Table 5.15 Analysis of future balance and surplus between water supply and water demand balance in the study area/10^9 m^3

Country	2025	2030	2040
Myanmar	19.42	22.82	14.8
Thailand	2.18	5.6	3.46
Cambodia	0.94	1.23	0.63
Laos	3.61	3.54	3.38
Vietnam	8.62	11.83	4.95

be effectively used, and the total water supply in the five countries is more significant than their water demands.

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Chapter 6
Water Linking to Food and Energy

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Abstract **Water, food, and energy resources are critical concerns to achieve the UN 2030 Sustainable Development Goals**. However, achieving food, energy, and water security is under increasing pressure due to population and economic growth as well as climate change. Climate change affects the regional precipitation and discharge in both time and space scales. Rice consumption increased about 5 times during 1961–2017, and energy requirements increased with an annual growth rate of 5–6% between 1990 and 2010 at the global scale. **This chapter studies the linkage of water-food and water-energy sectors as well as the nexus relationship in the Langcang-Mekong River Basin (LMR B)**. Agriculture is the main water consumer in LMRB, and expansion of irrigated cropland and agricultural intensification has significantly increased the irrigation water demand. The basin is an ideal location for developing and utilizing hydropower resources, and the hydropower potential is estimated at around 60,000 MW. Future climate change might decrease the regional hydropower potential, especially around the mainstream. Water demand for thermal power generation and fossil fuel extraction is increasing due to population growth and socio-economic development. Furthermore, biofuel production and crop planting

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areas both increased sharply in the Lower Mekong countries, especially in Vietnam and Thailand. **Water, food, and energy resources are strongly connected in the Mekong River Delta**. A nexus case study in the Mekong River Delta showed a strong connection among food, energy, and water systems. Rice yields will be vulnerable to extreme climate events, and the development of the energy sector will affect regional sustainability through nexus significantly. Specifically, the average total water withdrawal in 2050 was estimated to increase by 40% compared to that in the 2016 drought year and will be more than 3 times higher than the average withdrawal of 1995–2010.

6.1 Introduction

Water is a critical resource to food and energy supply. Demand for water, food, and energy is increasing due to population growth and economic development. The inter-linkage among these three resources is critical to support food and energy security and sustainable development. Understanding and managing these often-competing interests requires an integrated approach to achieve sustainable agriculture and energy production and ensure food and water security. Stakeholders in all three domains are thus focusing on water resources management due to the dependence of energy and food sectors on water. Agriculture is remaining the biggest water consumer, and its water consumption is highly affected by climate, crop patterns, diet, and technologies. Fossil fuel is still a main part of the global energy mix. Its extraction and production process such as fracking and biofuel are highly water intensive. Therefore, water linking to food and energy as well as their nexus relationship are critical to achieve long-term regional sustainability.

6.2 Water Linking to Food

6.2.1 Cropping System

The water resources of the Lancang-Mekong River Basin support the social and economic development of the countries in the basin, provide the suitable planting environment for crops, especially rice, and guarantee nutrition and development of the people. The river connects China with five Southeast Asian countries, Myanmar, Laos, Thailand, Cambodia and Vietnam and covers the entire area of Cambodia and Laos, 30% of Thailand and 20% of Vietnam. The water resources of the basin are vital to the rice cultivation in these four countries, which are also the main source of rice supply in more than 100 countries around the world.

The total agricultural area of Cambodia, Laos, Thailand and Vietnam is estimated to be 41.2 million hectares, of which 16.7 million hectares are allocated to rice fields, accounting for 41% of the total agricultural area. Thailand has the largest agricultural area, estimated at 22.1 million hectares, followed by Vietnam at 10.9 million hectares, Cambodia at 5.8 million hectares and Laos's 2.4 million hectares. Rice is the main planting system of the basin as the area allocated by each country accounts for 38–42% of the total agricultural area (Cosslett & Cosslett, 2017).

Rice cultivation in the basin has two periods, namely the wet season (May to October) and the dry season (November to April). Furthermore, rice is divided into three types: "lowland rain-fed rice" grown in lowland areas during the wet season; "upland rice" grown in upland areas during the wet season and about 1–2 months earlier than lowland rain-fed rice; and irrigated rice planted in the dry season (Mainuddin & Kirby, 2009). Compared with traditional rain-fed rice (which require 5–6 months of growth time and usually have lower yields), irrigated rice requires an average of 3–4 months of growth time, and thus more than one season can be planted each year and the production is higher. Farmers in Vietnam plant three- seasons of rice each year, while farmers in Thailand, Laos and Cambodia plant two seasons each year.

The basin also has a variety of upland crops, see Table 6.1. Maize (28% of the total area of upland crops), cassava (26%) and sugarcane (22%) are the three main crops, almost all grown under rain-fed conditions in Laos, Thailand and Cambodia. Crops growing areas in Cambodia can be divided into three categories: upland, lowland and flood plain. The main crops on the upland include: upland rice, cassava, corn and soybeans. In the lowlands, rice is the main crop, with some orchards and vegetables. In flood areas, two types of rice are planted, namely flood rice and recession rice. Rice in Laos is mainly produced through rain-fed, and supplementary irrigation is also available in some areas. Other crops include corn (such as sweet corn and animal feed), cassava, sugar cane, rubber and peanuts. Thailand's rice production can be self-sufficient and is a major exporter of several crops including rice, corn and cassava. Other crops include peanuts, vegetables, rubber and sugarcane. Vietnam is dominated by rice cultivation. Other crops include soybeans, corn, sesame and sweet potatoes. Irrigation in the Vietnam Delta is used to grow rice, upland crops and fruit trees. In the rainy season, the area of irrigated rice is estimated to be 141,684 ha, while in the dry season it is 76,184 ha (Mainuddin & Kirby, 2009; MRC, 2014).

However, farmers are currently abandoning rice cultivation and are starting to plant other crops such as corn, beans and fruits, which bring more income than rice cultivation. Therefore, the crop production department supports the shift from low-yield rice cultivation to more profitable crops. In 2019, the Mekong Delta provinces planned to convert 124,526 hm^2 of rice fields to other crop fields (Wang, 2018).

6.2.2 Irrigation

Agriculture is the biggest water consumption sector in the basin, expansion of irrigated cropland and agricultural intensification has significantly increased the irrigation water demand (Merme et al., 2014). This is especially due to the rice cultivation

Table 6.1 Main crop types in LMRB countries (adopted from Mainuddin & Kirby, 2009)

Country	Crop	Growing season	Growing period (days)
Laos	Lowland rice	June–October	130
	Dry season rice	November–March	130
	Upland rice	May–September	130
	Maize	May–September	125
	Sweet potato	August–December	125
	Cassava	April–January	270
	Mung bean	September–December	90
	Soybean	September–January	135
	Sesame	August–November	110
	Peanut	August–December	120
	Tobacco	August–November	110
	Cotton	May–November	195
	Vegetables and beans	September–December	95
	Sugarcane	May–February	280
	Watermelon	December–March	110
	Chillies	September–January	130
	Tea, Coffee	Perennial	
Thailand	Major rice	June–October	130
	Second rice	November–March	130
	Upland rice	May–September	130
	Maize	May–September	125
	Mungbean	September–December	90
	Cassava	April–January	270
	Sugarcane	May–February	280
	Soybean	September–January	135
	Groundnut	August–December	120
	Kenaf	April–September	150
	Cotton	May–November	195
	Sorghum	June-October	125
	Onion, garlic and shallot	September–December	95
	Potatoes	October–February	120
	Coffee, longan and pineapple	Perennial	
Cambodia	lowland rice	July–November	130
	Dry season rice	November–March	130
	Upland rice	May–September	130
	Maize	May–September	125
	Cassava	April–January	270

(continued)

Table 6.1 (continued)

Country	Crop	Growing season	Growing period (days)
	Soybean	September–January	135
	Potatoes	October–February	120
	Sugarcane	May–February	280
	Vegetables	September–December	95
	Mungbean	September–December	90
	Peanut	August–December	120
	Sesame	August–November	110
	Tobacco	August–November	110
	Jute or kenaf	April–September	150
Vietnam	Summer–autumn rice	July–November	120
	Winter–spring rice	November–March	120
	Spring–summer rice	April–August	120
	Maize	November–March	125
	Soybean	November–March	135
	Sweet potato	November–March	125
	Cassava	April–January	270
	Sugarcane	May–February	280
	Peanut	November–March	120

expansion in the primary rice production bases of the basin. Rapidly increasing irrigation water demand has caused heavy groundwater exploitation, a decrease of river flow and a local water crisis during the dry seasons (Macdonald et al., 2015; Thilakarathne & Sridhar, 2017). In addition, changes in precipitation patterns in the Mekong river basin may also increase supplementary irrigation even during the wet seasons (Yamauchi, 2013). Continuous groundwater overexploitation has led to rapid groundwater depletion and sea water intrusion as sea level rise in the Mekong delta, and potentially threatens crop production and food security under future climate change (Driel & Nauta, 2013; Rahman, 2014).

Nevertheless, it becomes increasingly difficult to maintain the current rice production level due to the intensive irrigation requirement. To solve this problem and achieve sustainable agriculture under projected climate change, water-saving technologies have been introduced to the local agro-ecosystem and guarantee food security in the Mekong river basin countries. Considering the decreasing surface water availability under projected climate, the Alternative Wetting and Drying (AWD) has been proposed and widely accepted as a water-saving technology for the sustainable water use for rice production (Ekkehard & Fiege, 2010; Quynh & Sander, 2015), especially in the major rice production regions of Vietnamese Mekong delta where more than 50% of total rice production and 95% of rice exported from Vietnam are produced (Lovell, 2019). However, AWD requires much higher field water management skills for the local farmers and is difficult to rapidly adopt in the basin (Mushtaq et al., 2006; Yamaguchi et al., 2017). Other agricultural adaptations include shifting the crop calendar, breeding drought-resistant crop cultivars and de-intensification of current multiple cropping systems, such as shifting from triple rice cropping to double rice cropping.

In addition to the agricultural adaptations for water saving and maintaining food production, transboundary water collaboration is also critical to the water management in the basin (Yuan et al., 2019). For example, dams and water diversion for agricultural irrigation in the upstream of the basin (i.e. Thailand) may cause severe water shortage and threaten crop production in the downstream delta, which experienced severe drought in 2016. Meanwhile, increasing population and rapid socioeconomic growth in the basin generate higher water demand and irrigation will also increase under the projected warmer climate. Transboundary collaboration to optimize the water distribution and lower the negative impact of potential drought risk in the Mekong river basin is crucial to water sustainability (Li et al., 2019; Yamauchi, 2013). Therefore, the Mekong River Commission (MRC) and the "Lancang-Mekong Cooperation Mechanism" were established for the water resource cooperation of dams and water diverting facilities in this region. However, this would also significantly impact the local ecosystem and fisheries industry along the river (Yoshida et al., 2020). Tradeoffs between agricultural production and ecosystem conservation should be carefully estimated (Chen et al., 2020).

6.2.3 Water Use in Livestock and Fisheries Sectors

In the basin, farm animals are raised in a conventional extensive way with low inputs. There is a significant discrepancy from lowland areas of the Mekong river to the upland and sloping areas (FAO, 2020). For example, cattle and buffalo are mainly raised in the central areas. While raising pigs and chickens important and common in highland areas. Large-scale farms of pigs and chickens are rare at the village level, and thus would not provide considerable employment opportunities in livestock productions. Meat demands are met mainly due to an ascended production scale instead of the production efficiency increase in the basin. For example, to increase production scale, Cambodians even raise livestock in rice-farming systems (ADB, 2012).

It is of importance to study water resources linking to fisheries in terms of their water availability (Irannezhad et al., 2020) and variety in the basin, in particular aquatic animals (Garrison et al., 2007) such as fish and shrimp. This has attracted attention because the Mekong river basin is the home to the largest inland-fisheries industry worldwide (Fig. 6.1). Specifically, statistical data show there are approximately 1,200 fish species inhabited within the Mekong river basin (second to the much larger Amazon river basin (Schmitt et al., 2019). *Wild* fish production reaches as high as approximately 2 million tons per year; meanwhile, raised fish production exceeds 2.5 million tons annually. These fish productions are mainly distributed in Laos and Cambodia (WBG, 2018), and support more than 70 million livelihoods in mainland southeast Asia. For example, in the Mekong river basin 96% of the population and 77% of poverty households typically worked in agricultural, forestry and fisheries industries.

Therefore, it is critical to investigate the water consumption and variety of the fisheries and livestock industry for sustainable water management. As the Mekong river basin is home to the largest fisheries inland-industry worldwide, its huge water consumption and the competence among fisheries, irrigated agriculture, livestock and hydropower generation for water resources become one of the biggest challenges for sustainable development in this basin. Moreover, water consumption and variety are subject to uncertainty under rapid socio-economic development, trade interaction and sustainability among developing countries within the "Belt and Road initiative".

Three aspects are stressed and recommended in previous studies: (1) There is a dearth of data in these regions. Water withdrawal and consumption accounting methods and datasets should be localized and suitable to adapt unique local conditions for the LMRB (Zhang et al., 2020). Uncertainty analysis such as inter-comparisons of different data and models should be developed and conducted to improve the reliability of the results and conclusions (Chen et al., 2021). (2) Fisheries and livestock water consumption should be considered for strategic planning at the river basin scale (Ziv et al., 2012). (3) Integrated Water Resources Management and international cooperation were suggested to be conducted and developed, such as the cooperation between Finland and Russia in the Vuoksi river basin (Jormola et al., 2016).

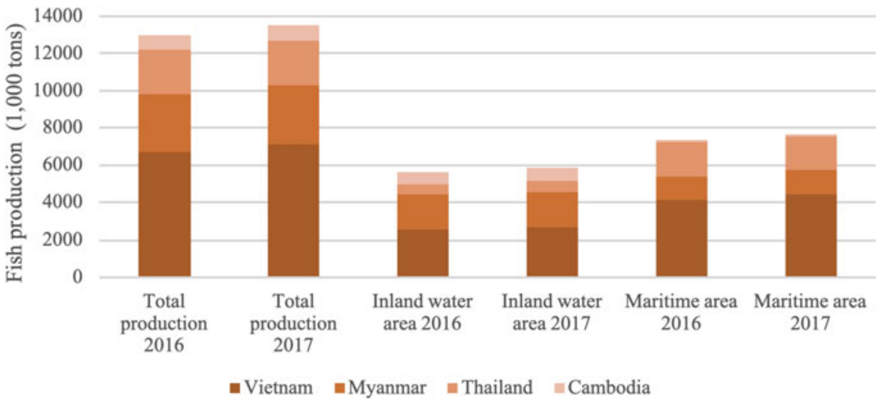

Fig. 6.1 Fish production in the main countries of LMRB during 2016–2017 (FAO, 2020)

6.3 Water Linking to Energy

6.3.1 Hydropower Development

Hydropower is a renewable and eco-friendly source of energy that makes significant contributions to meet the increasing global power demands. It accounts for 73% of the world's renewable power supply and has been widely recognized as a crucial component in the fight against climate change (Almeida et al., 2019; Latrubesse et al., 2017; Owusu & Asumadu-Sarkodie, 2016; Zarfl et al., 2019). However, the rapid construction of hydropower-driven dams worldwide has led to disputes over their negative environmental impact (Maavara et al., 2020; Sunday, 2020; Waldman et al., 2019).

The Lancang-Mekong River, which originates in the Qinghai-Tibet Plateau and flows through Myanmar, Vietnam, Laos, Cambodia, and Thailand (Fig. 6.2), is divided into two sub-sections: the mountainous Lancang River basin in China with a low population density and the flat and fertile Mekong River basin with a high population density. The Mekong River basin contributes to about 82% of the river's annual discharge (MRC, 2010). The Lancang-Mekong River Basin is an ideal location for developing and utilizing hydropower resources due to its strong topographic gradient, rugged terrain, and high flow volumes. Although the Mekong River basin is mainly covered by lowlands and floodplains, it still has considerable hydropower potential estimated at 60,000 MW (MRC, 2011). Pokhrel et al. (2018) estimated that the hydropower potential of the mainstem Lancang-Mekong River is ~53,000 MW with another ~35,000 MW from tributaries. However, only nearly 40% of the hydropower potential has been exploited so far with an installed capacity of around 24,000 MW (WLE-Mekong, 2018). Due to rapid socio-economic development and ascending power demands, the Mekong River basin is undertaking an unparalleled rate of dam construction (Pokhrel et al., 2018).

According to Pokhrel et al. (2018), the Lancang-Mekong river system is home to several large dam projects, some of which have been completed while others are under construction or planned (Fig. 6.3). The dams under commission are mostly located at the tributaries of the Mekong River. Among those planned are 15 dams in the main stem of the Lancang-Mekong river and several other hydropower dams are being planned in the tributaries of the Mekong River basin, including many in the Seong, Sesan, and Sre Pok basins. These basins constitute the largest sub-watershed of the Mekong and contribute ~17% of the Mekong's annual discharge with an estimated hydropower capacity of 9500 MW (Xue et al., 2011).

The availability of water resources and hydropower generation are likely to be affected by global warming (Arnell & Gosling, 2013; Hoang et al., 2019), which is projected to cause higher climate variability and more extreme weather conditions. This could have implications for the water-energy-food nexus (van Vliet et al., 2016; Zhang et al., 2017) and alter the positive synergy relationship between hydropower generation and irrigation supply (Zeng et al., 2017). Storage for hydroelectricity generation can improve water supply for irrigation. Dams can be operated to build

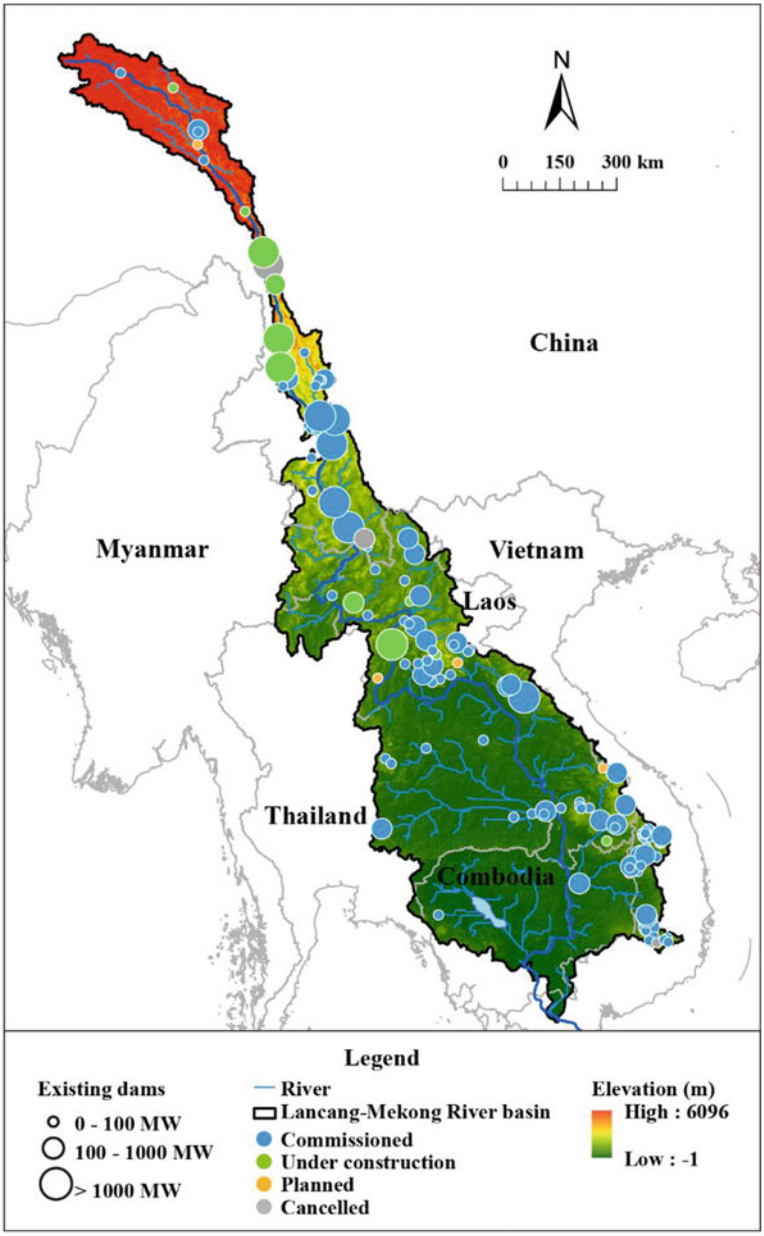

Fig. 6.2 The location of existing dams in the LMRB. The dam data is from Water, Land and Ecosystems (WLE-Mekong, 2018)

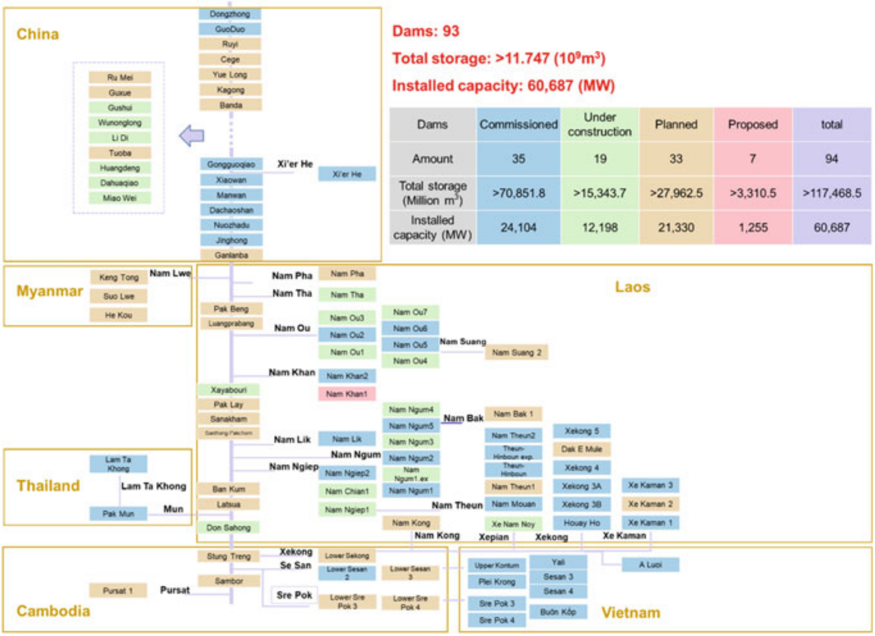

Fig. 6.3 The quantity and distribution of existing dams in the Lancang-Mekong River basin (WLE-Mekong, 2018)

up a high hydraulic head and then release the water to produce hydropower. At the same time, hydropower dams can provide reliable water resources for irrigation supply during the dry season (Zewdie et al., 2019).

Meng et al. (2021) conducted an integrative analysis to assess the impact of global warming scenarios of 1.5 and 2 °C on the co-benefits between hydropower and irrigation in the Mekong River basin. The study employed a hydrological, techno-economic, and agricultural modeling framework to evaluate the effects of these scenarios. The results showed that the gross hydropower potential in the Mekong River basin is 3,069, 2,936, 2,677 and 2,791 MW under each of the historical period, the scenario of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0), for the whole Mekong River basin. The gross hydropower potential is larger under the scenario of 2 °C (RCP6.0) than 1.5 °C (RCP6.0) although the gross hydropower potential under both scenarios of global warming is smaller than that in the historical period. Most areas in the Mekong River basin show decreasing trends of the hydropower potential under 1.5 and 2 °C global warming scenarios, especially in the grids around the mainstream. The highest hydropower potential during the historical period is located along the Mekong River mainstream where the hydropower potential reduces most under the global warming scenarios, see Fig. 6.4. The study shows that the Mekong River basin's hydropower generation is expected to decrease under both scenarios. The total production provided by potential hydropower plants for the entire study area is 44.19×10^6, 2.10×10^6, 3.33×10^6 and 1.84×10^6 GWh under each of the historical period, the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0). The hydropower generation under 2 °C (RCP6.0) is less than both scenarios of 1.5 °C (RCP2.6) and 1.5 °C (RCP6.0). However, when considering the effects of protected areas, the total hydropower generation will be 9.69×10^5, 1.32×10^6, 9.39×10^5 and 6.85×10^5 GWh. The total production decreases by 3.05 and 29.34% under 1.5 °C (RCP6.0) and 2 °C (RCP6.0), respectively, when excluding the protected areas but increases by 36.66% under the scenario of 1.5 °C (RCP2.6) compared to the historical period1. Therefore, policymakers should consider balancing hydropower generation with forest coverage area in nationally determined contributions.

6.3.2 Other Energy Sectors

Water consumption for energy purposes includes thermal plant cooling, extraction of fuels (e.g. oil, gas, and coal), and biofuel crops irrigation. The energy demand in the Mekong river basin increased with rate of 5–6% per year between 1990 and 2010, and this trend was projected to continue in the near future (ADB, 2012). Annual growth rate of electricity demand from 2010 to 2018 was 5%, which is twice the world average. Coal-fired power generation is favored by most countries in the Mekong due to the relatively low costs. Even with rising concerns over emission and pollution, power generated by fossil fuel including coal and gas still represents more than 50% of the total generation (IEA, 2019). Taking the Mekong Delta in Vietnam as an example, there will be 14 new coal-fired power plants in 2030 with a water demand of 79.44 million m^3/day, which is about 15 times of the water demand in 2016 (Tuan, 2018) (Fig. 6.5).

Heat is converted into electricity in the thermal power plant, most of which use steam as the main heat. However, not all the heat is converted, and the "waste heat" requires water to be cooled down and goes back to the system again. Therefore, the amount of cooling water is highly dependent on the cooling methods. There are three typical cooling systems: once-through/open-loop systems, wet-recirculating/closed-loop systems, and dry cooling systems. The once-through method usually withdraws a large amount of water to pass through the heat exchanger, and returns most of the water to the source. The returned warm water is usually concerned with the thermal pollution of the water body. The closed-loop method adopts cooling towers or cooling ponds to cool down the water by transferring the heat to the air. Some amount of water is thus lost due to evaporation, and the rest is reused in the steam condenser. The drying cooling method uses air instead of water to cool the steam and thus consumes the minimum amount of water and has the lowest environmental impact. Tradeoffs among different types of cooling systems are shown in Table 6.2. There is still a lack of a comprehensive assessment of the cooling water use in the Lower Mekong river basin countries due to limited data of power plant cooling methods in these countries.

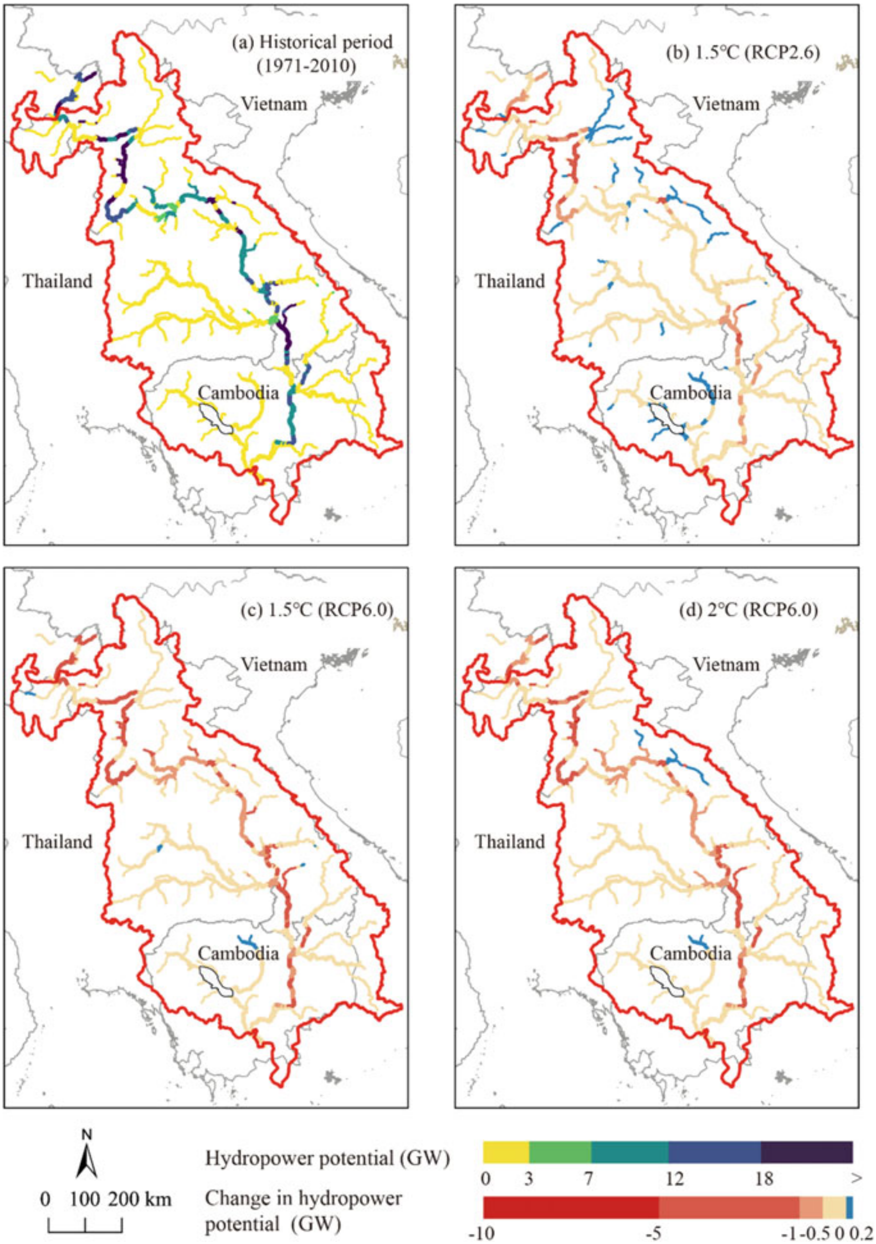

Fig. 6.4 Hydropower potential (GW) during the historical period, and the differences between the historical period and the 1.5 and 2 °C global warming scenarios

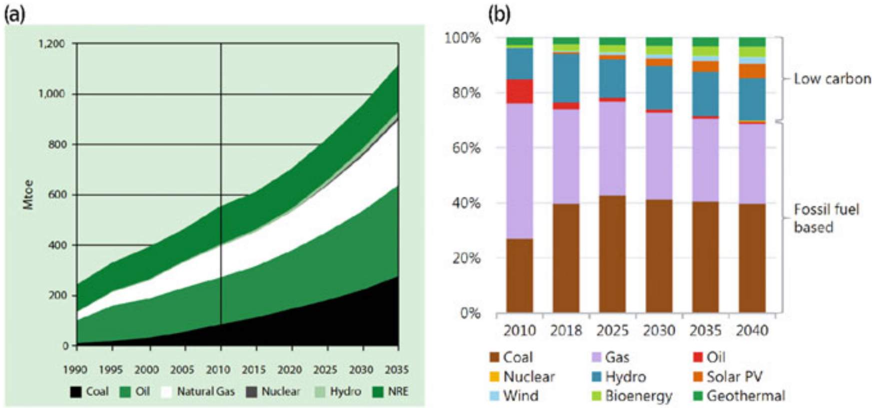

Fig. 6.5 Energy demand (**a**, adopted from ADB, 2013) and electricity generation by sources (**b**, adopted from International Energy Agency, 2019)

Table 6.2 Cooling system tradeoffs (adopted from Rodriguez et al., 2013)

Cooling methods	Water withdrawal	Water consumption	Plant efficiency	Capital cost	Ecological impact
Once-through	High	Moderate	Low	High	High
Close-loop	Moderate	High	Moderate	Moderate	Moderate
Dry cooling	None	None	High	Low	Lower

Mineral resources in the Mekong river basin include gold, copper, lead, zinc, phosphate, potash, oil and gas, coal and gemstones, which remain largely unexploited (MRC, 2021). Oil, gas, and coal are the three main resources for energy production. Fossil fuels are projected to be the dominant energy due to the increasing demand in the lower Mekong countries. There will be an increase in the use of coal, especially Thailand and Vietnam, according to the International Energy Agency (IEA, 2019). In the lower Mekong Basin, the largest thermal generation source is the Mae Moh coal mine in Thailand. Thermal generation sources of Vietnam are mainly located in the northern part. Laos' coal resources are relatively abundant with for example the Hongsa coal mine in Sainyabuli Province (ADB, 2008). As for the oil and gas, Cambodia and Laos have no significant production, while Myanmar could be a primary gas producer with a reserve of 10 trillion cubic feet in 2012. Thailand is a producer of oil and gas with a proved reserve of 0.3 thousand million barrels and 0.2 trillion cubic meters in 2018, respectively. Vietnam has emerged as an important oil and natural gas producer in the Mekong River basin with a proved reserve of 4.4 thousand million barrels and 0.6 trillion cubic meters in 2018, respectively (BP, 2019). Water withdrawal for fuel extraction is not as intensive as the total industrial water withdrawal and only represents 4% of the basin withdrawal (FAO, 2012). However, detailed water withdrawal data is not available in the Mekong River Basin.

Bioenergy is the mainstay of Southeast Asia's renewable energy source (IEA, 2019). Traditional biomass products are the main sources of energy and access to electricity in Laos, Cambodia, and Myanmar due to the less-developed infrastructures than Thailand and Vietnam (Soutullo, 2019). Biofuel production increased sharply in the Lower Mekong countries especially in Vietnam and Thailand with an annual increase rate of 30% in Thailand during 2008–2018 (BP, 2019). The planting area of biofuel crops such as cassava and sugarcane thus expanded significantly (FAO, 2021), see Fig. 6.6.

Biofuels consume water mainly through crop irrigation. Take Vietnam as an example, water cultivation for cassava was about 9801 m^3/ha/year. In 2015, the total amount of water for cassava cultivation was about 5.55 km^3, while water used for processing and ethanol production, 0.086 km^3, was relatively small (FAO, 2018). Blue, green, and grey water footprint of sugarcane and cassava in northern Thailand (Kongboon & Sampattagul, 2012) are shown below (Fig. 6.7).

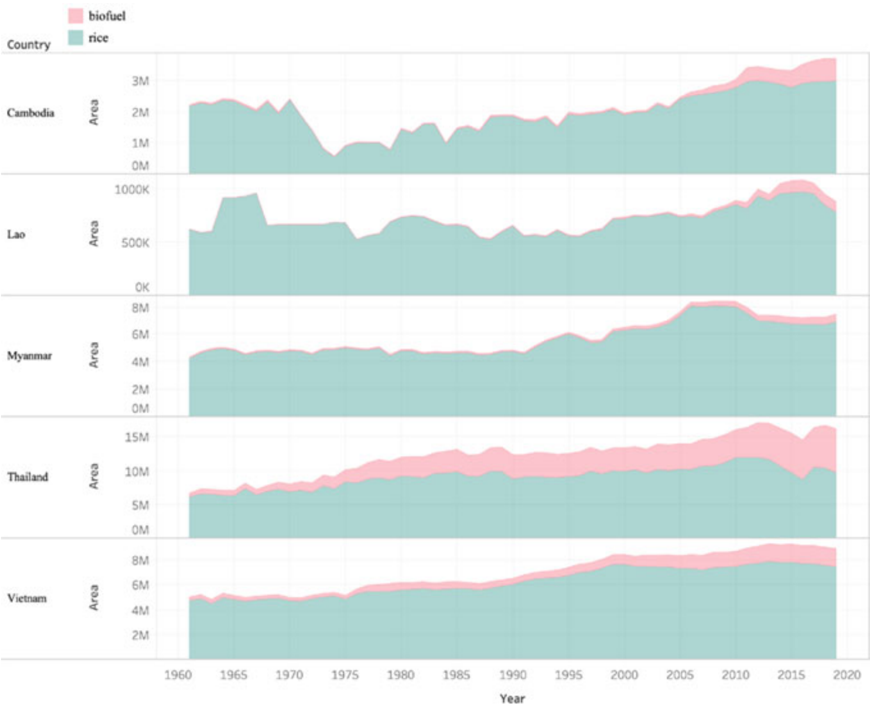

Fig. 6.6 Biofuel crops and rice area in the Lower Mekong River Basin countries (based on data from FAO, 2021)

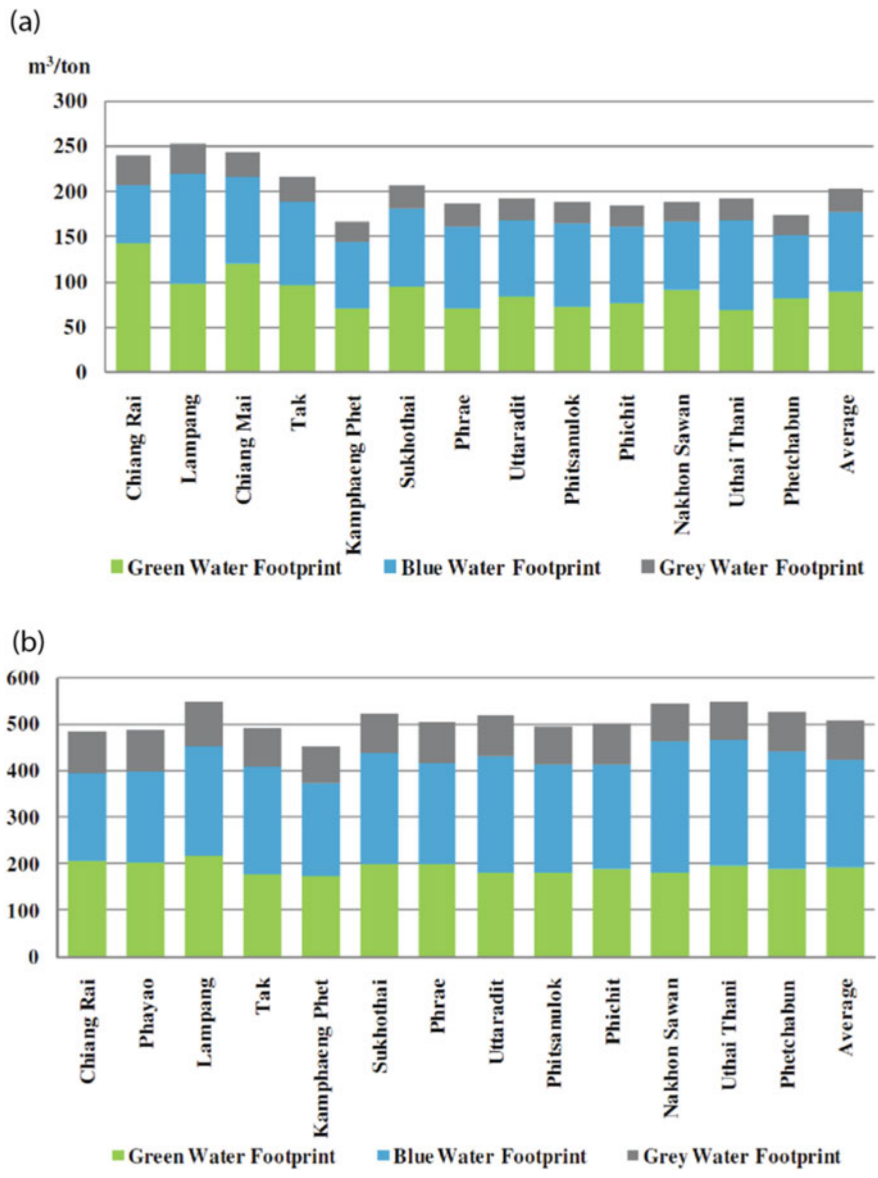

Fig. 6.7 Water footprint of sugarcane (**a**) and cassava (**b**) in northern Thailand (adopted from Kongboon & Sampattagul, 2012)

6.4 Water-Food-Energy Nexus

6.4.1 The Importance of the Nexus

The United Nations 2030 Sustainable Development Goals prioritize water, food, and energy resources (Liu et al., 2018). However, climate change, population growth, and economic development are putting increasing pressure on achieving food, energy, and water security. By 2050, food demand is expected to increase by 50% due to population growth, urbanization, and personal income increases (FAO, 2017). Similarly, energy demand is projected to increase by a factor of 1.7–2.8 above current usage due to socio-economic developments (Van Vuuren et al., 2019). Climate change exacerbates the situation by making water a growing constraint for food production and energy generation. As a result of climate change, an additional 120 million people are projected to be at risk of undernourishment (FAO, 2017) (Fig. 6.8).

The Bonn 2011 Conference introduced the nexus approach, which is recognized as an effective way to achieve sustainable management of food, energy, and water resources by integrating management and governance across sectors and scales (Hoff, 2011). Significant progress has been made in understanding the interaction among food, energy, and water systems, which has laid a solid foundation for theoretical research and practical processes of sustainable development (Liu et al., 2020). A case study in the Mekong River Basin highlights the importance of the nexus approach in managing water, food, and energy resources for sustainable development.

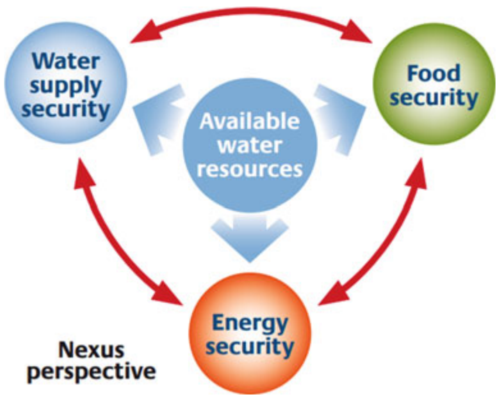

Fig. 6.8 Food, water, and energy nexus (adopted from Hoff, 2011)

6.4.2 Regional Case Study

Mekong River Delta

The Mekong River Delta (MRD) is situated downstream of the Mekong River Basin (Fig. 6.9) in Vietnam, covering an area of 40,500 km^2 and home to 17.8 million people in 2018 (WUR, 2020). The delta experiences two seasons: the dry season (November to April) and the wet season (May to October). The average annual rainfall ranges from 1400–2200 mm, and the average monthly flow varies from 6.1 to 69.2 km^3 (Tuu et al., 2019). As the primary source of rice production in Vietnam, the delta plays a crucial role in the nation's food security, accounting for over 56% of rice production in 2015. It is also a significant contributor to food trade in Southeast Asia and globally (WUR, 2020). The Mekong river delta is not solely dependent on hydropower as an energy source. Due to the nation's high growth power demand, which increased more than 10% per year during 1990–2010, the delta is planned as a thermal power center with 14 new coal-fired plants by 2030 (KEP, 2015; Yoshida et al., 2020).

The delta is currently facing several challenges due to climate change and socio-economic development. Over the past 30 years, the annual rainfall has increased by 30%, and the average temperature has risen by 0.5 °C. Climate change is expected to cause further temperature increases ranging from 1.1 to 3.6 °C, with projected increases in maximum and decreases in minimum monthly flow (WUR, 2020). Additionally, the planned thermal plants are expected to have adverse environmental impacts and intensify water conflicts among various water-use sectors. Therefore, it

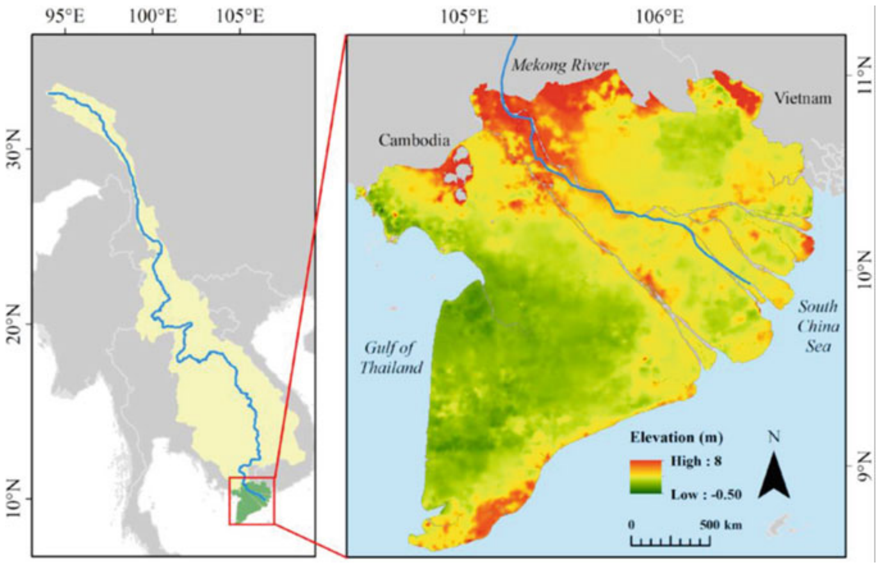

Fig. 6.9 The Mekong River Delta

is crucial to have a comprehensive understanding of the impacts of climate change and socio-economic development through the Food-Energy-Water nexus to achieve regional resource security and long-term sustainability.

An IWRM-Based Model

An integrated management model (Wang et al., 2019) was used to assess the effects of climate change and socio-economic development on the Food-Energy-Water Nexus. The model, which was developed using system dynamics methodology, captures the interactions among various subsystems at an annual scale. It was designed for Integrated Water Resources Management (IWRM) and includes the main water use sectors: agricultural, municipal, industrial, environmental, and recreational water uses, as well as water supply. These sectors are linked through water allocations and various land, water, and technical management policies. The model simulates water balance by considering water demands, allocation, and consumption, and generates socio-economic and environmental indicators for sustainability assessment at the basin scale.

This study aimed to quantify the changes in the Food-Energy-Water Nexus under different climate change and socio-economic scenarios by analyzing the agricultural, industrial, water use, and supply sectors. Rice cultivation accounts for 80% of surface irrigation withdrawal and is a major driving factor of water competition in the Mekong river delta. Coal-fired power is expected to be the primary energy source, occupying over 50% of power capacity. Therefore, the agricultural and industrial sectors simulate rice yield and thermal power generation, and water withdrawal is used for irrigation and cooling purposes. The water sector connects food and energy sectors through water allocation based on available water each year, and competition between food and energy sectors occurs when their demands cannot be fully satisfied. Various RCP-SSP scenarios (RCP: Representative Concentration Pathway, SSP: Shared Socioeconomic Pathway) are used to drive changes in rice planting area, thermal power demand, available water for allocation, and climate variables such as precipitation. These changes further affect irrigation and cooling water requirements, rice yield, and power generation (Fig. 6.10).

Scenario Setup

This study comprehensively explored the future conditions of the Food-Energy-Water Nexus by adopting RCP-SSP scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The scenarios describe socio-economic and climate futures, with SSP representing socio-economic futures and RCP representing climate futures. The integration of these two futures allows for a comprehensive exploration of the future conditions of the Food-Energy-Water Nexus.

To assess the concurrent effects of socio-economy and climate, this study employed five representative SSP-RCP combinations. These combinations are as follows:

1. SSP5-8.5: This combination represents future pathways with high greenhouse gas emissions and a high challenge to mitigation and adaptation.

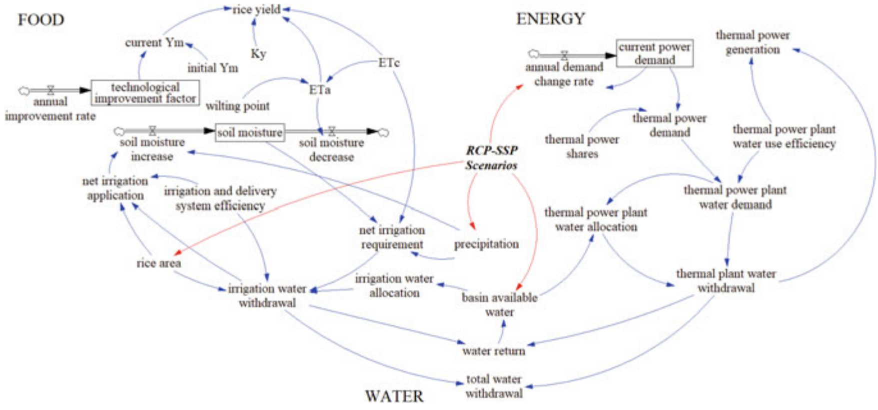

Fig. 6.10 The modified basic structure of the IWRM model used for MRD

2. SSP4-6.0: This combination is in the range of medium forcing pathways with a high challenge to adaptation.
3. SSP3-7.0: This combination represents medium–high future mitigation and forcing pathways.
4. SSP2-4.5: This combination is the middle ground, combining intermediate challenges for mitigation and forcing signals.
5. SSP1-2.6: This combination represents the case with low societal vulnerability and forcing level

Main Findings

Figure 6.11 displays the rice yield, power generation, and precipitation of five SSP-RCP scenarios from 2020 onwards. On one hand, the increased yield trends of three rice types in all scenarios were due to technical improvements based on historical data. However, maintaining the yield growth trend is a challenging task, and the Vietnam government recognizes technical improvement, especially biotechnology, as a decisive strategy to achieve long-term food security. On the other hand, yields of all three rice types were vulnerable to future climate and socio-economic changes, which will severely impact autumn rice yields with many extremely low yield events projected by all five scenarios. Finally, winter rice was projected to have many extreme yields, especially in the SSP4-6.0 scenario. The increasing number of low yield events resulting from water shortage could also trigger conflicts with energy and other water use sectors during growing seasons. Therefore, it is recommended to highlight mitigation strategies for the nexus instead of a single sector.

SSP5-8.5 was the most resource and energy-intensive scenario, with a power demand projection that was about 10 times higher than the generation in 2010. SSP1-2.6, on the other hand, was oriented towards low energy and resource consumption, and thus had the lowest projection, which was about 2 times higher than the generation in 2010. The other three scenarios fell between SSP1-2.6 and SSP5-8.5 in terms

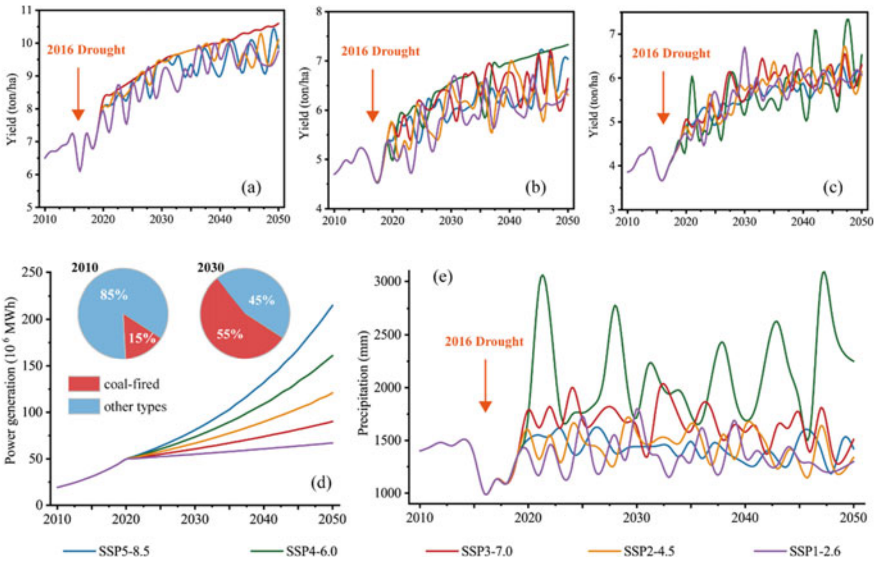

Fig. 6.11 The yield of spring (**a**), autumn (**b**), and winter (**c**) rice, power generation (**d**), and precipitation (**e**) in different climate and socio-economic scenarios

of power generation. The Electricity and Renewable Energy Authority in Vietnam estimated that national energy consumption would increase by about four times from 2017 to 2050, which is in the middle range of the five scenarios in this study. It is worth noting that coal-fired power plants will generate more power in the future, increasing from 15% in 2010 to 55% in 2030, as Mekong river delta will be Vietnam's thermal power center and the coal-fired plant is favored by the national government. However, this growth of coal-fired power plant generation will inevitably increase water use for cooling purposes and intensify conflicts with irrigation use during growing seasons.

Figure 6.11e illustrates the effects of five scenarios on precipitation during growing seasons. While SSP1-2.6 predicted a downward trend, the other four scenarios projected an increase in precipitation, with several years of extreme wetness, such as the SSP4-4.6 scenario. Overall, future precipitation is expected to increase, but more extreme high and low events are also anticipated. As a result, the Mekong River Delta is expected to face an increasing risk of flooding during the wet season and water shortages during the dry season.

Figure 6.12 displays the total water withdrawal, rice irrigation, and coal-fired power plant withdrawal. On one hand, the growth of power generation and the ratio of coal-fired plants will lead to an increase in total water withdrawal (Figs. 6.11d and 6.12a). The average value of total water withdrawal in 2050 is expected to be more than three times higher than the average withdrawal during the 1995–2010 period, with a 40% increase from the 2016 drought year withdrawal. On the other hand, climate change is expected to result in increased precipitation during growing seasons, which might reduce irrigation water demand in wet years and provide more

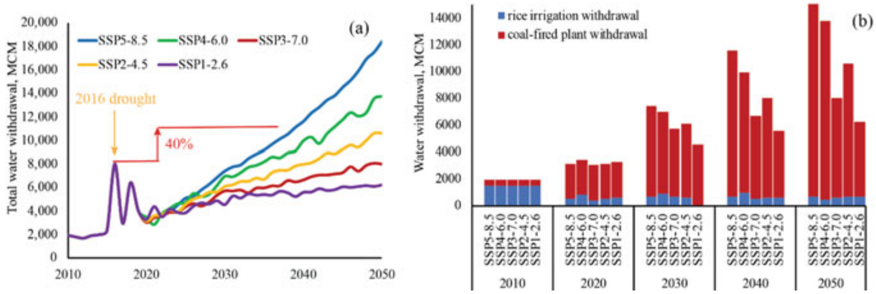

Fig. 6.12 Water withdrawal of the MRD (**a**) and rice and coal-fired plant withdrawal (**b**)

available water for expanding coal-fired plants. However, high cooling water demand in dry years could trigger conflicts between the food and energy sectors. All existing and planned plants in the Mekong River Delta assume once-through cooling method. Therefore, it is suggested to use water-saving technologies such as air cooling and non-surface water instead of the once-through method for new thermal power plants to mitigate the impacts of climate change and socio-economic development on the nexus system.

Figure 6.13a illustrates the relationship between rice yield, coal-fired power generation, and water withdrawal under five climate change and socio-economic scenarios in the Mekong river delta. The trends in the three-dimensional relationship of the five scenarios reveal a strong connection among food, energy, and water systems in the Mekong river delta. Figure 6.13b shows a clear linear trend between coal-fired power generation and water withdrawal under five scenarios. This trend indicates that water is a constraint of the coal-fired power plants, and water withdrawal is also affected by the amount of power generated by coal-fired plants. The strong connection between the water and energy sector also implies possible pressure on the local water system due to power plant development, which has already received significant attention. Figure 6.13c shows that rice yield in the Mekong river delta increases with water withdrawal when it is lower than 8000 MCM (million cubic meters), indicating that rice cultivation in the region heavily relies on irrigation and is vulnerable to water availability. However, when water withdrawal exceeds 8000 MCM, yield seldom increases as energy generation accounts for most of the water withdrawal, particularly under SSP5-8.5 and SSP4-6.0 scenarios. The relationship between the food and energy sectors is relatively weak. The linear trend observed between coal-fired plant generation and water withdrawal is due to water availability, which affects both rice yield and coal-fired plant generation. Therefore, water plays a key role in the Food-Energy-Water Nexus as it connects both the food and energy sectors in the Mekong river delta.

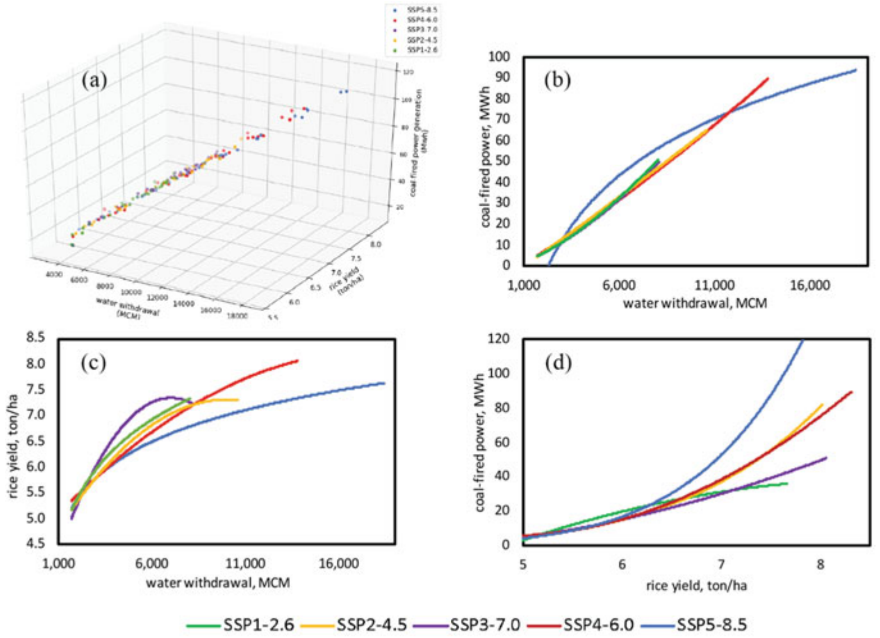

Fig. 6.13 FEW nexus (**a**), food-energy (**b**), food-water (**c**), and energy-water (**d**) relationship in the MRD

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Chapter 7
Water Hazards: Drought and Flood

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Abstract **Droughts and floods are the main threats to the Lancang-Mekong River Basin (LMRB)**. Drought mainly occurs during the dry season, especially in March and April, in the LMRB. The "dry gets drier" paradigm performs well in the LMRB, specifically in the Mekong Delta. Further, flood frequency and magnitude, which are determined by heavy rain, are also increasing in the LMRB. **Droughts and floods show obvious seasonal and regional characteristics in the LMRB**. The LMRB is a well-known rainstorm-flood basin. Floods in the LMRB are mainly caused by heavy rain. The LMRB is dominated by regional floods, and basin-wide floods rarely occur. From upstream to downstream, the flood peak and flood volume have shown increasing trends. Meanwhile, moving further downstream, the flood season ends later. In the upstream areas, floods are mainly concentrated in the period from July to October, with the highest probability of floods occurring in August. For the downstream areas, the flood season is from August to October. **Climate change is one of the major factors affecting the LMRB's droughts and floods**. Global warming is an indisputable fact. Under global warming, extreme hydrological events show a tendency to increase. Climate models have suggested a future potential for increased flood frequency, magnitude, and inundation in the LMRB by 10–140%, 5–44% and 19–43%, respectively. Although the severity and duration

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of droughts are also increasing, the differences in drought indicators projected by different climate models are significant. **Hydropower development was another major factor affecting droughts and floods in the LMRB**. Large-scale hydropower development has drastically changed streamflow characteristics since 2009, causing increased dry season flow (+150%) and decreased wet season flow (−25%), as well as reduced flood magnitude (−2.3 to −29.7%) and frequency (−8.2 to −74.1%). Large-scale reservoirs will have a profound impact on hydrological characteristics, droughts and floods, agriculture, fisheries, energy supply, and environmental protection in the LMRB. **Coupling climate models and hydrological models is the main way to study the impact of climate change and reservoir operation in the LMRB**. Climate change indirectly affects hydrological characteristics by affecting meteorological parameters, while reservoirs can directly change the propagation from meteorological extreme events to hydrological extreme events by releasing/storing water in different situations. Hydrological models are the link connecting and quantifying the coupled effects of climate change and reservoirs. More studies are needed to develop a comprehensive understanding of the future impacts of climate change and reservoir operation on extreme events in the LMRB, as well as adaptation and mitigation measures.

7.1 Introduction

Droughts are generally defined as prolonged periods with well below normal rainfall in a region, leading to an extreme shortage of water (Gonzalez-Hidalgo et al., 2009), and floods are defined as intensive rainstorms which can quickly increase streamflow in rivers where excessive water overflows out of the river and leads to surface water flooding. The flood process has several characteristics, including the flood peak, flood volume and flood duration. The frequency of those characteristics during the flood process are often different but mutually correlated (Luo et al., 2021).

Droughts and floods have received widespread attention because they could have substantial social and economic consequences. With the unprecedented impact of climate change and human activities in recent decades, the terrestrial water cycle is becoming non-stationary, leading to more extreme events. This will affect the hydrological characteristics of rivers, with impacts on industrial, economic and social development. As one of the most important transboundary rivers in the world, the Lancang Mekong River Basin (LMRB), especially the Mekong River Basin (MRB), suffers frequent hydrological disasters. According to the Emergency Events Database (EM-DAT), the LMRB recorded 173 floods and 23 droughts between 1990 and 2016, affecting 148.5 million people and causing a total economic loss of 61.4 billion US dollars.

At the same time, the LMRB will face two major challenges in the twenty-first century: changes to hydrological characteristics brought by climate change, and the impact of rapid hydropower expansion on extreme events (Liu et al., 2022). A significant increase in basin-wide temperatures and changes in monsoon patterns has been suggested by future climate projections, which is expected to cause an increase in extreme rainfall intensity and frequency and ultimately drive flood changes in the basin. Meanwhile, rapid hydropower expansion at an unprecedented rate in this century also has a huge impact on the LMRB. Considering that this change will affect the lives of nearly 237 million people, it is necessary to comprehensively review the combined impacts of climate change and reservoir operation on floods and droughts in the LMRB.

This chapter aims to provide a comprehensive review of the impact of climate change and reservoir expansion on floods and droughts in the LMRB. Section 7.2 explains the characteristics of LMRB droughts and floods during the historical period, and Sect. 7.3 explores the influence of future climate change on droughts and floods. Section 7.4 reviews the impact of reservoir operation on droughts and floods, and discusses the potential for reservoirs to adapt to and mitigate extreme events.

7.2 Characteristics of Droughts and Floods in the LMRB

7.2.1 Drought Characteristics

Drought is a natural disaster, defined as a significant deviation from normal hydrologic conditions such as rainfall, soil moisture or runoff (Mishra & Singh, 2010). Generally, droughts can be divided into four categories according to their nature and effects as meteorological, agricultural, hydrological and socio-economic droughts. Drought is one of the most serious disasters in the Mekong River Basin (Zhang et al., 2020a, 2020b) and the middle LMRB is trending to intensified drying (Fig. 7.1). Since the beginning of the twenty-first century, the Mekong River has been affected by several major drought events (Guo et al., 2017; Son et al., 2012). Understanding the spatial and temporal characteristics of drought can greatly facilitate drought management and risk reduction.

7.2.1.1 Spatial Characteristics of Drought in LMRB

Drought in the Mekong River has apparent spatial heterogeneity and high correlation with latitude (Li & Chen, 2015; Li et al., 2013). Based on 0.25° × 0.25° resolution daily precipitation data from the Global Land Surface Data Assimilation System (GLDAS), Zhang et al., (2020a, 2020b) found that high-incidence areas of extreme agricultural drought were in Yunnan Province, China and northwestern Thailand and high-vulnerability areas were distributed in the middle and southern LMRB. Combining high incidence with high vulnerability, the middle of the LMRB and the Sesan, Srepok and Sekong river basins (3S) are high-risk areas of agricultural drought. Liu et al. (2020) found that dry extreme events have increased significantly over the northeastern Thailand, most of Cambodia and Myanmar, particularly for

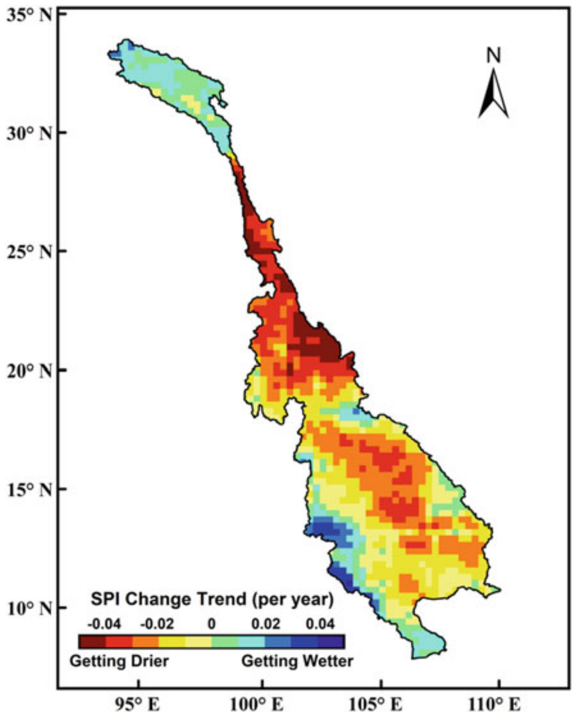

Fig. 7.1 Trend of Standardized Precipitation Index (SPI) change from 1979 to 2019 in the LMRB. Data was obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5)

southern Cambodia and the Mekong Delta where the frequency of extreme drought is around 10%. In general, the occurrences of drought events are mostly in the lower LMRB, followed by the upper and middle LMRB (Tang & Cao, 2020).

Through principal component analysis and K-means clustering of daily precipitation observation data from 35 weather stations from 1960 to 2005, it was found that there is a strong linkage between climate zones and spatial characteristics of drought, while the high-risk areas of drought are mainly located in the middle and southern LMRB (Li et al., 2013). Because rainfall stations in the LMRB are sparse and unevenly distributed, satellite precipitation data are usually used as alternative sources. The satellite precipitation products from the Tropical Rainfall Measuring Mission (TRMM) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) have been proven to be reliable data sources for studying drought in this area (Luo et al., 2019; Zeng et al., 2012).

Son et al. (2012) used the Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) and monthly surface temperature data from the National Aeronautics and Space Administration (NASA) to monitor agricultural drought from November 2001 to April 2010, and found that moderate and severe droughts occurred over the whole lower LMRB. Based on two long-term satellite-based precipitation products, namely the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data

Record (PERSIANN-CDR) and CHIRPS, Guo et al. (2017) found that hydrological drought occurred more frequently in the north and south of the LMRB, especially in the Mekong Delta which had experienced long-term and extreme drought events. Further, the spatial distribution of drought was mainly affected by precipitation and temperature, while precipitation was the dominant factor in the distribution of dry extremes (Li et al., 2013). Kang and Sridhar (2021) found that 68.4–76.1% of incidences of increased drought were caused by decreased precipitation or increased temperature. In terms of water vapor fluxes, the Tibetan Plateau Monsoon (TPM) and South Asian Monsoon (SAM) are the major factors that affect the occurrences of drought in the upstream and downstream regions of the LMRB respectively (Tang & Cao, 2020).

7.2.1.2 Temporal Characteristics of Drought in LMRB

Besides the obvious spatial characteristics, drought in the LMRB also has distinct temporal characteristics, and there are two major modes of drought development. One is the evolution from severe drought at the beginning of the dry season to moderate drought at the end of the dry season occurring in the Mekong Delta. The other is the gradual evolution of drought that intensifies and expands and occurs in the upper LMRB (Zhang et al., 2020a, 2020b).

Through wavelet transformation, it was found that drought in most of the LMRB shows an evolution with a major period of 3–7 years, which is likely related to El Niño-Southern Oscillation (ENSO) (Li et al., 2013). Meanwhile, the results of Empirical Mode Decomposition (EMD) showed that more than 60% of drought changes are caused by inter-decadal changes in precipitation (Li et al., 2013). Through monitoring of dry extremes, the main drought events identified were in 1983, 1991–1994, 1998–1999, 2005 and 2015–2016 (Guo et al., 2017). Focusing on droughts in different seasons, agricultural drought occurs mainly in the dry season, corresponding to the ripening stage of rain-fed rice and the heading stage of winter-spring rice (Son et al., 2012). However, generally, drought occurs most frequently in the boreal spring, especially in March and April (Li et al., 2013; Sridhar et al., 2019).

When considering the entire basin, drought in the LMRB decreased during 1977–2010. However, the Mekong Delta, with the most drought events in the LMRB, is trending towards drier conditions in some areas. Zhou et al. (2011) analyzed the precipitation data of 38 weather stations in the LMRB from January 1977 to August 2010 from the National Oceanic and Atmospheric Administration (NOAA) Data Sharing Network and the Mekong River Commission (MRC), and found that extreme droughts in the LMRB have decreased, especially in the dry season. After reconstructing the runoff of the Mekong river from 1557 to 2005 using tree rings, it was found that there has been a significant increase in runoff in the last 30 years (Yang et al., 2019a, 2019b). Kang and Sridhar (2021) applied the Soil and Water Assessment Tool (SWAT) model to simulate soil moisture, runoff and evapotranspiration in the LMRB using meteorological forcing data from the Coupled Forecast System Model version 2. Based on the results of the Modified Palmer Drought Severity

Index (MPDSI), Standardized Soil Moisture Index (SSI) and Multivariate Standardized Drought Index (MSDI), drought was shown to increase in most of the lower LMRB while decrease in west of the mid LMRB during 1953–2016. Furthermore, a study based on the latest version of TRMM Multi-Satellite Precipitation Analysis (TMPA) real-time product (3B42RTv7) to achieve real-time Variable Infiltration Capacity (VIC) Macroscale Hydrologic modeling showed that 30% of areas experienced severe hydrological drought from January 2015 to December 2018 and severe drought would become normal in the LMRB (Zhang et al., 2020a, 2020b). Similarly, Jing et al. (2020), using Gravity Recovery and Climate Experiment (GRACE) data, found that drought in the upper part of LMRB had a slight increasing trend, while drought in the lower had an insignificant increasing trend from 2003 to 2016.

The change in drought is also related to human activities especially in the Mekong Delta. Based on the Temperature Vegetation Dryness Index (TVDI), most of the Mekong Delta has experienced moderate and even severe drought in the dry season (Phan et al., 2020). In 2016–2018, drought intensity became more severe and the increase in severity mainly occurred in rice fields (Tran et al., 2019). The increase of drought intensity in the Mekong Delta was attributed to human activities. Transforming land from perennial trees and forests to residential and public transportation land, led to the increase of drought in the central part of the Mekong Delta, while an increase of aquaculture land and mangrove forests led to a decrease in drought in coastal areas (Phan et al., 2020).

7.2.2 Flood Characteristics

Due to the sporadic nature of floods, the characteristics of floods in the LMRB are summarized as follows in order to provide a basis for the countries along the LMRB to formulate flood control measures.

7.2.2.1 Causes of Floods

The causes of floods in the main stream of the LMRB are mainly determined by factors such as topography and landforms, precipitation and runoff. The topography and geographical location of the LMRB determine different characteristics of floods generated in the basin. Due to geographical location and the influence of southwest monsoon, precipitation in the upper and lower reaches of the LMRB is significantly different (Kingston et al., 2011). Spatially, the annual precipitation amount increases gradually from north to south, with local patterns due to topographic effects. Furthermore, surface runoff can be divided into rainwater runoff and snowmelt runoff (Wang et al., 2021). The former is caused by rainfall and the latter by melting snow. Runoff is a basic element of the hydrological cycle, which causes the change of river water regimes. Rainfall contributes to 80–90% of runoff in the LMRB, which is the major factor influencing flood occurrence (Delgado et al., 2012; Lauri et al., 2012; Wang et al., 2022).

The LMRB has a monsoon climate, and torrential rains are the direct cause of floods (Darby et al., 2016; Yang et al., 2019a, 2019b). The Lancang River basin is a transitional climate zone from plateau temperate climate to subtropical climate. The middle and lower reaches of the Lancang River basin are typical alpine and canyon landforms with alternating mountains and gorges, and the terrain is undulating. The intensity of the heavy rain in this area is relatively large and it is the main flood-hit area in the Lancang River basin. The Mekong River Basin is a subtropical or tropical climate zone, and the weather systems that cause torrential rain are mainly tropical convergence zones, tropical cyclones and tropical depressions. The torrential rains in the Mekong River basin mainly occur from July to October. The upper reach of the Mekong River basin is a mountainous and hilly area, with a small number of mountain plains and basins intermittently distributed. The width of the river valleys alternates repeatedly. The valleys in the basins and alluvial plains in the dam area are open and gentle. The terrain is low and flat, and the downstream canyons are easily blocked by water. Therefore, it is easy to be flooded here, during the flood season. The middle and lower reaches of the LMRB and the Mekong Delta are mainly plains and lowlands, which are also vulnerable to flooding (Chen et al., 2020b; Wang et al., 2022).

The LMRB in Phnom Penh receives a large amount of water from its main tributary, Tonle Sap Lake. Tonle Sap Lake is an important flood buffer and natural reservoir (Chang et al., 2019; Try et al., 2022). The depth and area of the Tonle Sap Lake varies greatly between the rainy and dry seasons. During May to September, when the water level of the Tonle Sap Lake is lower than that of the LMRB, 10% to 18% of flood water in the LMRB will flow backward into the Tonle Sap Lake through the Tonle Sap River, greatly reducing the peak flow of the LMRB (Chang et al., 2019; Try et al., 2019). Thus, the regulation of Tonle Sap Lake, the storage of many river branches and the backflow of tides play a considerable role in influencing the main river channel. With Phnom Penh as its apex, the Mekong Delta has dense river networks. The river channels have changed from alluvial to siltation, and the water system is unstable, complex and volatile. The flow rate is slow, and the sediment is gradually silting up, forming a series of wide alluvial plains and wetlands. Due to the low and flat terrain, the discharge capacity of the river channel is seriously insufficient relative to the huge flood volume of the river section above Stung Treng. When the water level at the three stations of Kratie, Kampong Cham, and Takhmau is high, the flood of the LMRB passes through a large number of distributary channels or siltation channels to the floodplain behind the embankment, and the flood lasts for on average 19–48 days per year (Xu et al., 2020).

7.2.2.2 Temporal Characteristics of Floods

Floods in the LMRB are mostly formed by continuous heavy rains or rainstorms. Rainstorm volume increases from north to south in the basin. Downstream areas are likely to flood even in December.

In the Lancang River basin, the annual maximum flood is likely to occur from July to October, as precipitation during this period exceeds 80% of the annual precipitation (Kingston et al., 2011; Yang et al., 2019a, 2019b). At the same time, there are occasional floods in early- and mid-October. This is due to the relatively stable atmospheric circulation in the central and western regions of Yunnan Province in early- and mid-September, and the probability of heavy rain is relatively small. In October, cold air from the north becomes active, and the southwest airflow retreats to the west of Yunnan. The two air currents converge, resulting in heavy rain, which then causes floods. Tropical cyclones from the South China sea are one of the reasons for torrential rains in the Mekong River basin (Chen et al., 2019, 2020a). The flood period in the upper reaches of the Mekong River basin is from June to November, among which August is the most likely month for the annual maximum flood to occur. The flood period in the middle and lower reaches of the Mekong River basin is from June to December, and the probability of occurrence of the annual maximum flood is almost the same in August and September.

7.2.2.3 Spatial Characteristics of Floods

Floods caused by rainstorms in the LMRB show obvious spatial differences. The peak discharge per unit area is close to the limit value for global rain flood rivers (O'Connor & Costa, 2004). To consider spatial variation, we selected long-term daily streamflow observation data for seven hydrological stations from north to south in the LMRB, including Yunjinghong, Chiang Sean, Luang Prabang, Vientiane, Mukdahan, Pakse and Stung Treng. Table 7.1 shows the statistics of flood peak and flood volumes at these selected stations. The mean annual flood (MAF) of these seven stations ranges from 6710 to 54,000 m^3/s. The measured maximum peak discharge (MAX) over the measured years ranges from 13,900 to 78,100 m^3/s, while the mean annual 30-day flood volume (MAX30d) ranges from 13.8 to 112.9 billion m^3. From the above statistical data, it could be found that the peak and volume of floods were not only large, but also increasing from north to south in the LMRB.

The LMRB has a large latitudinal span, and the direction of the river and the shape of the basin are essentially parallel to the monsoon activity route. Therefore, the LMRB is dominated by regional floods, and the probability of basin-wide floods is small (Wang et al., 2022). Floods at upstream and downstream of Vientiane are basically discontinuous (MRC, 2007). Since hydrological measurement data became available, the flood from August to September 1966 was the most extensive flood in the LMRB, and its impact was mainly limited to the Lancang River basin and the upper and middle reaches of the Mekong River basin. Vientiane City and Nongkhai City were the regions most severely affected by the flood, and they experienced a

Table 7.1 Statistics of flood peak and flood volume at seven selected stations in LMRB

Station name	MAF (m^3/s)	MAX (m^3/s)	Year of MAX	MAX30d (billion m^3)	Data record
Yunjinghong	6710	13,900	1966	13.8	1953–2007
Chiang Sean	10,278	29,300	2006	19.1	1960–2016
Luang Prabang	14,346	25,200	1966	26.3	1939–2016
Vientiane	16,673	26,633	2008	35.2	1913–2016
Mukdahan	28,404	38,900	1923	64.8	1923–2016
Pakse	37,253	57,800	1978	82.7	1923–2016
Stung Treng	54,000	78,100	1939	112.9	1910–2007

catastrophic flood. Figure 7.2a shows distribution of the flood range and severity in the LMRB from 1985 to 2019. During the flood season, flood-prone zones are mainly distributed in the Mekong River basin, especially the downstream (Hoang et al., 2019). The most frequent flood-prone zone is mainly located in the "3S" river basin (i.e., Sekong, Se San, Sre Pok). Moreover, severe floods with high flood peaks or large flood volumes are more often to occur in the "3S" river basin (Wang et al., 2022). The flood-prone zones are mainly distributed in Tonle Sap Lake and the Mekong Delta, followed by the Mun-Chi River Basin in eastern Thailand and the Songkhram River Basin, upstream of Nakhon Phanom station.

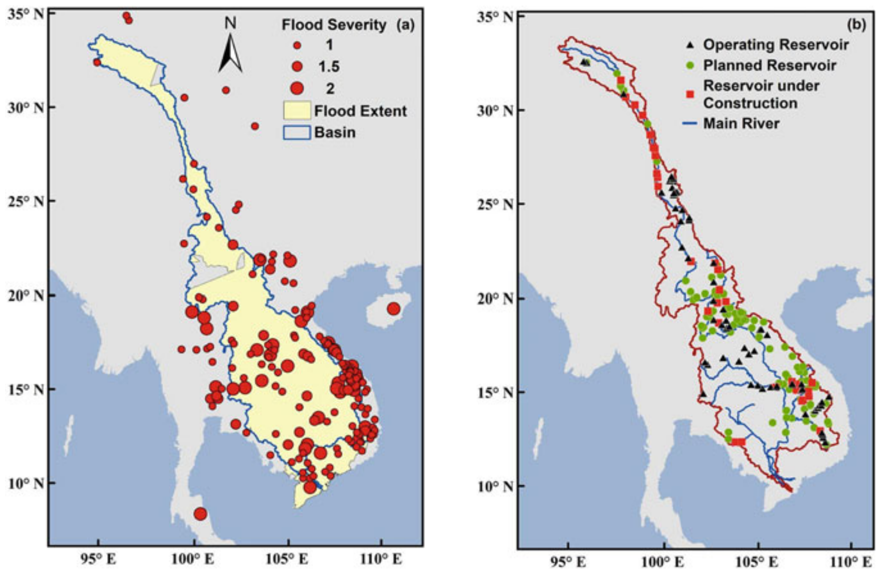

Fig. 7.2 **a** The distributions of flood extent and severity in LMRB during 1985–2019. Data were obtained from http://floodobservatory.colorado.edu/, for definitions of flood severity see Chen et al. (2020b). **b** The distributions of reservoirs in LMRB

7.3 Climate Change Impacts on Droughts and Floods

7.3.1 Climate Change Impact in LMRB

Climate change is now considered to be one of the main threats facing the planet in the twenty-first century. The IPCC AR6 report pointed out that global surface temperature increased from 1850–1900 to 2010–2019 with a best estimate of 1.07 °C, and the rate of global warming has continued to accelerate (IPCC, 2021). In general, this warming intensifies the global hydrological cycle, which means an increase of global average precipitation and evaporation (Mishra & Singh, 2010). As a basin with a typical monsoon climate, the LMRB has also been greatly affected by climate change.

Projections based on climate models suggest a significant increase in basin-wide temperatures and changes in monsoon patterns (Pokhrel et al., 2018). The annual average temperature and precipitation respectively was predicted to increase by 0.6–1.4 °C and by 1.2–8.6%, respectively, for the years 2032–2042 compared to the baseline of 1982–1992 (Lauri et al., 2012). Compared to the baseline of 1971–2000, the daily average temperature during 2036–2065 was predicted to increase by 2.4 °C and 1.9 °C from Representative Concentration Pathway (RCP) 8.5 and RCP4.5 ensembles under CMIP5 climate projections, respectively; while annual precipitation from the two ensembles increased by −3 to 5% (RCP8.5) and 3–4% (RCP4.5) with an average of 3% across all scenarios (Hoang et al., 2016). The change patterns for the 95th and 99th percentile precipitation showed more prominent increases under Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) projections, though the change patterns for the 90th percentile precipitation were comparable to that of the annual precipitation (Wang et al., 2017). Under high-resolution atmospheric GCMs (AGCMs), the annual precipitation of the future climate (2075–2099) would increase by 6.6–14.2% (Try et al., 2020a).

The temperature increase tends to be greater in the southern and northern parts of the basin, whereas the patterns for annual precipitation varied with GCMs and emission scenarios but increases were more likely in the Lancang River basin (Hoang et al., 2016; Lauri et al., 2012). Patterns for precipitation changes were different even under the same emission scenario: e.g., the largest increase was in the middle basin for three GCMs, while in the northernmost and southern parts for the remaining GCMs (Lauri et al., 2012). Under CMIP5, precipitation was projected to increase in some areas while decrease in others, though the overall pattern was increasing (Hoang et al., 2016).

7.3.2 Climate Change Impacts on Drought

GCMs are an advanced tool for assessing the impacts of climate change and have been widely used for drought projections (Abbasian et al., 2019; Tabari et al., 2021).

Several climate change scenarios are used to describe the likely effects of future climate change, such as the Special Report on Emission Scenarios (SRES), the Representative Concentration Pathways (RCPs) and the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014). The effect of climate change under different scenarios is assessed below.

The SRES were originally used to describe climate change and its future effects (IPCC, 2007). Although the SRESs are currently rarely applied, the research method of combining the impact of population, energy, and economy on climate change is still valuable. SRES A1B represents very rapid economic growth with increasing globalization and a balance of fossil intensive and non-fossil fuels. The impact of climate change in this scenario on the drought of the Mekong is controversial. Based on precipitation and temperature from Japan Meteorological Agency's GCM in the periods of 1979–1998 and 2080–2099, Kiem et al. (2008) simulated future hydrology by using the grid-based University of Yamanashi distributed hydrological model (YHyM) and found that there were fewer days of drought in the LMRB, meaning that drought will be alleviated in the future. However, when Falloon and Betts (2006) used the Hadley Centre Global Environment Model version 1—Total Runoff Pathways (HadGEM1-TRIP) to simulate global river flow changes under this A1B scenario, they found that although the projected annual runoff of the Mekong River increases by 40.3%, this increase reflects in a large increase in the monthly maximum flow and a large decrease in the monthly minimum flow. Hirabayashi et al. (2008) claimed the increase of drought from 2001 to 2030 mainly occurs in the middle LMRB, but the drought increases in the entire basin from 2017 to 2030, especially in the last 20 years of the twenty-first century. Scenario SRES A2 represents less rapid economic growth than SRES A1 but more rapid population growth. The consensus on the future drought of the Mekong in this scenario is that although climate change has increased annual runoff, there may be water deficit in the dry season because the increase in runoff occurs mainly in the wet season. Van Huijgevoort et al. (2014) found a decrease in low discharge for most models and by combining with three GCMs and five large-scale hydrological models, indicated drought would intensify in the LMRB. SRES B2 means development following environmentally, economically, and socially sustainable pathways. Under this scenario, Deb et al. (2018) estimated water resources based on five commonly used GCMs and the Hydrologic Engineering Center—Hydrologic Modeling System (HEC-HMS) models. Their conclusions were basically consistent with the conclusions under SRES A2, which is that the available water resources will decrease in the dry season but increase in the wet season. However, drought may become serious even in the wet season. Yamauchi (2014) found that drought duration and severity will generally increase in the wet season in the lower Mekong River under a scenario similar to SRES B2 proposed by the MRC.

In recent research, the SRES used frequently in earlier studies, have been replaced by RCP scenarios, describing radiative forcing and concentrations of greenhouse gases until the year 2100. Hoang et al. (2016) found that climate change reduced the frequency and extent of extreme drought of the Mekong River, when simulating extreme drought using the distributed hydrological Visual MODFLOW (VMod) model (Lauri et al., 2012), forced by five GCMs and under two RCPs. Their results suggest that the projected drought will decrease in 2036–2065 compared to 1971–2000. However, Sridhar et al. (2019) used SWAT and VIC models to simulate flows under the same RCP scenarios, and found that all results showed a significant reduction in the dry season flow and more severe drought, although the overall flow of the Mekong River would increase. Meanwhile, Thilakarathne and Sridhar (2017) found that most GCMs indicated increased probabilities of severe drought scenarios in the entire Mekong Basin, and the lower Mekong Basin was forecast to experience a higher risk of drought based on precipitation of 15 GCMs from NASA Earth Exchange Global Daily Downscale Predicted (NEX-GDDP). Based on four regional climate models (RCMs) (HadGEM3-RA, SNU-MM5, RegCM4 and YSU-RSM) and SWAT, the severity, duration, and frequency of drought in the Srepok basin located in the 3S area would increase. Meteorological, agricultural, and hydrological drought events were predicted to increase from 13% to 43%, 14% to 44%, and 22% to 40% respectively, under RCP 8.5 compared to 1980–2005 (Sam et al., 2019). Reduced drought but increased spatial heterogeneity were suggested by the result of a geomorphology-based hydrological model (GBHM), and southwestern China and the Mekong River estuary may suffer more severe drought (Li et al., 2021).

In the latest research into the effects of climate change on drought, SSPs, which consider the changes in global society, demographics and economics, are now being used as important inputs for the latest climate models. However, only a few studies have analyzed Mekong drought based on SSP scenarios. Zampieri et al. (2019) used the Annual Green Water Resources indicator (defined as the squared mean divided by the squared standard deviation of annual precipitation) time series to study droughts on a global scale under the SSP5-RCP8.5 scenarios, and found that the LMRB will become drier despite the increase in precipitation. Similarly, anthropogenic forcing was suggested to increase the risk of extreme and severe drought under SSP3-RCP7.0 and SSP5-RCP8.5 scenarios (Zhang et al., 2021). Whitehead et al. (2019) integrated RCP and SSP scenarios to simulate the flow and water quality of the Mekong River, but different SSP scenarios had no effect on lower flow because the model mainly focused on water quality. Future research on the impact of climate change on the drought in the LMRB should consider different SSP scenarios. By 2100, the range of changes in various socio-economic scenarios may be greater than the range of changes in various forcing levels (Arnell et al., 2019).

7.3.3 Climate Change Impacts on Floods

Climate change induced flood risks have been one of the challenges affecting global safety and sustainable development. The LMRB is one of the many flood-prone areas in Asia and has the highest flood-induced fatality in the world. Climate change has been one of two major challenges to its water resources in the twenty-first century. Understanding the impacts of climate change on floods in this region will help to plan and manage its water resources and provide guidance to disaster prevention and mitigation.

7.3.3.1 Relationship Between Climate Change and Floods

Climate change affects floods, both directly and indirectly, i.e., rainfall, sub-surface flow, and groundwater (Fang et al., 2014). For the direct effects (i.e., the main way), the anomaly in atmospheric circulation such as ENSO and monsoon changes can cause regional rainfall change (Räsänen & Kummu, 2013; Yang et al., 2019a, 2019b), while moisture increases in the atmosphere under global warming, causes an increase in the magnitude and frequency of rainfall (Kunkel et al., 2013). For the indirect effects, landcover (e.g., desertification) and soil property changes (e.g., soil erosion) under climate change scenarios can affect rainfall-runoff processes and thus can produce quicker and larger flood peaks (Bronstert, 2003).

In the LMRB, the monsoon climate dominates its hydro-climate conditions (Yang et al., 2019b). Two monsoon systems, i.e., the Indian summer monsoon (ISM) and Western North Pacific Monsoon (WNPM) (Delgado et al., 2012; Yihui & Chan, 2005), regulate the monsoon rainfall in the rainy season, leading to over 80% of the annual precipitation (Costa-Cabral et al., 2008) during May to October in the basin, and 80–90% of the discharge in the lower Mekong (Delgado et al., 2012). More importantly, the interannual variability of the rainy season precipitation in the LMRB is significantly modulated by co-variability of the ISM and WNPM (i.e., monsoon combined effect, donated as ISWN), other than individual effects (Holmes et al., 2009; Yang et al., 2019a, 2019b). When the ISM and WNPM are stronger (weaker) than normal, the combined effect is stronger (weaker) than normal. Also, the monsoons in this basin further interact differently with ENSO and are coupled to ENSO cycles where the coupling strength can be changed over time and with the Australian monsoon (Delgado et al., 2012; Lau & Wang, 2006). For example, during the warm phase of ENSO, the ISM and WNPM are found to weaken; the WNPM is most affected during the decay of the warm phase of ENSO, while the ISM is mostly affected during the ENSO development. Further, the linkage of the ISM and ENSO have dramatically reduced, but the linkage of the WNPM and ENSO have strengthened since the 1970s (Räsänen & Kummu, 2013; Wang et al., 2001; Wu & Wang, 2002).

Usually, the annual flood period, flood volume and annual flood peak decreased during El Niño and increased during La Niña (Räsänen & Kummu, 2013). During El Niño (La Niña) years, the flood start date was also delayed (advanced) from the average, while the flood end dates advanced (delayed). For the monsoons, the WNPM positively connects annual maximum discharge and flood season average discharge in Kratie and other stations in the southern parts of the LMRB, while the ISM has less influence on the interannual flood regime in these stations (Delgado et al., 2012). On average, the flood start date is advanced (delayed) by 8–12 days, Q10 increases (decreases) by 7.4–14.4%, and flood volume increases (decreases) by 9.0–17.5% during the strong (weak) monsoon years in over half of the monsoon impacted regions (Wang et al., 2022).

7.3.3.2 Flood Change in the Future

Under CMIP5 projections, the high flow (Q_5) during the period of 2036–2065 was projected to increase at all considered stations in the LMRB with the range of 5–8%, when compared to the baseline period of 1971–2000, but this was also projected to slightly reduce in some scenarios with −6 to −1% (Hoang et al., 2016). Further, the extremely high flow represented by yearly peak discharges also exhibited substantial increases, meaning both the magnitude and frequency of annual peak flows were projected to increase in the future. For the ISIMIP projections, the flood frequency increased at a higher rate (10–140%) than that of the flood magnitude (5−55%) (Wang et al., 2017).

By using AGCMs, the flood magnitude in the LMRB would be more severe than in the present climate by the end of this century. The increase of precipitation could lead to an increase of the high flow (Q_5) by 13–30%, of the peak inundation area by 19–43% and the increase of peak inundation volume by 24–55%, while no significant change was predicted to occur on peak flood timing (Try et al., 2020b). Under the scenario of the global average temperature increasing by 4 °C, different patterns of sea surface temperature significantly affected the variation of flood inundation in the future (2051–2110) in the Tonle Sap Lake and Vietnamese Mekong Delta. Extreme flood events (50-year, 100-year, and 1000-year return periods) showed the discharge, inundation area and inundation volume increased by 25–40%, 19–36%, and 23–37%, respectively (Try et al., 2020a).

In the Cambodian lowlands and Vietnamese Mekong Delta, where climate change and sea-level rise strongly alter the delta flood dynamics, RCMs based simulations projected that average and maximum water levels and flood duration would increase in 2010–2049, when compared to the baseline period of 1997–2000 (Västilä et al., 2010). When compared to the historical baseline period of 1971–2000, climate change based on CMIP5 suggested that the annual maximum water level in the future period (2036–2065) increased by 10–15% at Chau Doc, 2–8% at Long Xuyen, and less than 5% at Can Tho, with higher changes in wet years (Triet et al., 2020). The flood extent also separately increased by 1, 3 and 7% in the dry, normal and wet years for the future period of 2036–2065, while the inundation depth increased by 10–40 cm during the same period.

Climate change will remarkably alter flooding in the LMRB, which can be revealed from the model projections. A generally increasing pattern in flood peak inundation will potentially cause greater economic losses and death. Flood control and disaster reduction strategies including flood forecasting and flood control improvement are therefore urgently needed.

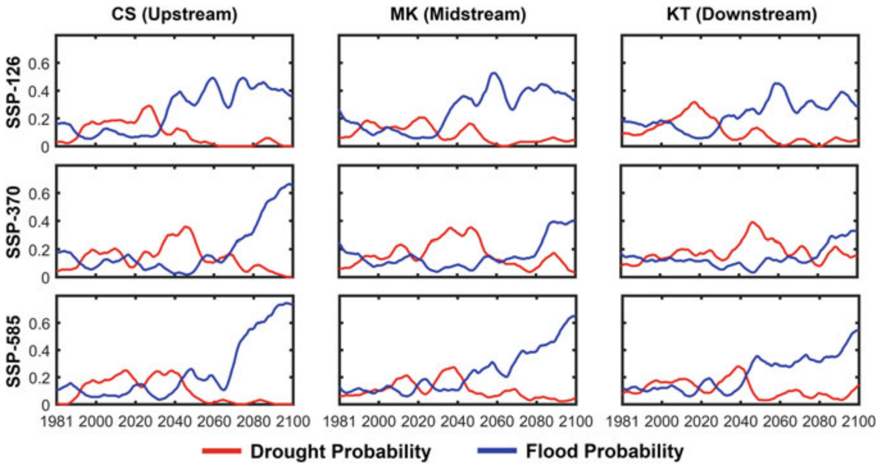

Fig. 7.3 Time series of drought probability and flood probability at the three representative stations during 1981–2100 in LMRB under the impact of climate change (CMIP6). The probability is calculated from the 30-year moving value (Fig. 7.3 was redrawn according to the data of Yun et al., 2021a)

7.4 Impact of Reservoir Regulation on LMRB

In order to tackle the increase in extreme events (e.g., drought and floods) under climate change, as well as to meet the increased demands of energy and agricultural irrigation from these developing countries in the basin due to rapid urbanization and population explosions, reservoirs in LMRB have expanded with an unprecedented rate in the past decades (MRC, 2017). Before 2008, the LMRB was one of the basins least affected by human activities in the world, with the active reservoir storage capacity accounting for only 2% of the annual streamflow (Kummu et al., 2010). In the following ten years, a large number of reservoirs were successively constructed and put into operation. The total storage capacity of the 103 large reservoirs under operation by the end of 2021 in the LMRB reached a staggering 100.3 km^3, accounting for 23% of the annual flow (according to the Greater Mekong Dam Database (GMDD), https://wle-mekong.cgiar.org/maps/). These reservoirs have profoundly altered the hydrological systems of the LMRB.

7.4.1 Observed Changes in Streamflow

The most discernible impact of reservoir operation in the LMRB is the changes to the seasonal flood pulse. Researchers have been concerned about the hydrological impact of the Lancang River basin dams because of their transboundary effects. Although many news and media outlets (Campbell, 2009; Stone, 2010) claimed that drought in the downstream basin might be caused by the construction of the upstream dams, most studies (Li et al., 2017; Yun et al., 2020) based on actual observations indicated there were limited impacts from upstream reservoirs (active storage capacity of 0.72 km^3) before 2010.

Cochrane et al. (2014) showed that the dry season (February to May) flow of Chiang Sean station during 1991–2010 increased significantly, while there was almost no change in the wet season flow, compared to the period 1961–1990, and a similar trend was observed at Vientiane station. At the same time, Pakse and Stung Treng stations located in the downstream LMRB experienced a limited increase in dry season flow and an abnormal decrease in wet season flow, which may be caused by ignoring the difference in precipitation and land use changes during different periods. In addition, other studies (Li et al., 2017; Lu et al., 2014) have also reached similar conclusions, and attributed the increased dry season streamflow at Chiang Sean station to the upstream dams.

Subsequently, more reservoirs had a greater impact on the streamflow of the LMRB (Han et al., 2019; Räsänen et al., 2017; Yun et al., 2020). Li et al. (2017) reported the critical impact of the upstream dams on downstream dry-season flows, which have increased dramatically as far as Kratie station in Cambodia. Räsänen et al. (2017) found that the streamflow at the upstream LMRB decreased by 32–46% during the wet season, and increased by 121–187% during the dry season in 2014 compared with 1960–1990. Moreover, Han et al. (2019) concluded a 95% contribution to streamflow changes from human activities at Yunjinghong station in China since 2008. Yun et al. (2020) pointed out that the impact of newly constructed reservoirs in the LMRB during 2009–2016 was tremendous in the upstream, and reservoir construction in the downstream LMRB had a greater impact on streamflow in the lower LMRB.

The total storage capacity of the LMRB's reservoirs under operation in 2021 was 57.7 km^3, which is six tenths of the total reservoir capacity in the LMRB. Most of these reservoirs are located in Laos, Thailand, Cambodia, and Vietnam. Some of these reservoirs are used to divert water to hydropower plants, downstream river sections, and adjacent tributary basins, to increase water head for more hydropower generation. For example, some reservoirs in Thailand are used to divert water, which increases the complexity of downstream research. In general, the numerous downstream tributary reservoirs have reduced seasonal streamflow changes. Piman et al. (2013a) found that when considering 23 reservoirs aimed at maximizing hydropower generation in the 3S area (Laos, Cambodia, and Vietnam), the dry season flow will increase by 63%, and the wet season flow will decrease by 22%. Yun et al. (2020) pointed out that the annual streamflow changes downstream of Mukdahan station would be affected more by the reservoirs downstream of Vientiane station (−3 to 8%) instead the reservoirs in China (−2 to 4%) during 2009–2016.

In addition, diversions have been associated with reduced flows downstream of dams, as well as flow augmentation in tributaries (e.g., Baird et al., 2015; Chanudet et al., 2016). For example, the Nam Theun 2 dam (completed in 2010, Laos) enables diversions from the Nam Theun river into the Xe Bang Fai river, resulting in an 83% (from 220 to 486 m^3/s) increase in natural mean annual flow at the Xe Bang

Fai river. Today, downstream releases from Nam Theun 2 are just 2 m^3/s, less than 1% of its mean annual inflow of 238 m^3/s, which affects the livelihoods of over 110,000 people (Hecht et al., 2019). At the same time, similar diversion has also been observed in other tributaries, including Houay Ho (Laos) and Yali Falls (Vietnam). Diversions to raise water levels in the Nam Ngun 1 reservoir have drastically reduced dry-season flows in the Nam Song River (Hecht et al., 2019). Ruiz-Barradas and Nigam (2018) indicated that extensive irrigation diversions in the Mun-Chi basin of northeastern Thailand resulted in an abnormal phenomenon of increased precipitation and decreased flow at same time in this area.

When evaluating the comprehensive impact of the LMRB's reservoirs, basin-wide hydrological models agreed that the reservoir will mainly affect seasonal flow fluctuations, including reducing the wet season streamflow and increasing dry season streamflow. Hoanh et al. (2010) investigated the impacts of 6 upstream dams in China and 81 downstream dams in Thailand, Laos, Cambodia, and Vietnam (including 11 mainstream dams), and concluded that the wet season flow will be reduced by 8–17% and the dry season flow will increase by 30–60% by the 2030s. Simulation results from Piman et al. (2013b) showed that 88 future reservoirs will increase Kratie's dry season flow by 28% and decrease wet season flow by 9%. Lauri et al. (2012) indicated that 126 future reservoirs with hydropower generation strategy will lead to an increased dry season (+160%) and decreased wet season (−24%) flow at Kratie station. Based on comparison with actual observations and simulation results considering 86 reservoirs, Yun et al. (2020) pointed out that reservoirs in the LMRB reduced the streamflow variability by increasing dry season streamflow (+15 to + 37%) and decreasing wet season streamflow (−2 to −24%) between 2009–2016. Shin et al. (2020) used a basin-wide river-floodplain-reservoir modeling system to directly evaluate the impacts of 86 existing dams across the LMRB and found that while the effects of dams on downstream flood patterns was minimal until 2010, the impacts has substantially increased since then because of new dam construction.

7.4.2 Reservoir Impact on Extreme Events

Streamflow change caused by the rapid hydropower expansion have affected many aspects of the LMRB's river ecosystem, including changes in hydrological extreme events (droughts, floods).

Recent observations (Li et al., 2017; Räsänen et al., 2017) indicated that the flood season in the LMRB has been delayed due to the seasonal storage buffer created by the reservoirs. At the same time, Yun et al. (2020) based on observation, found that reservoir operation during 2009–2016 reduced flood risk in the LMRB, while climate change increased the flood magnitude and frequency by up to 14% and 45%, respectively; reservoir operation reduced flood magnitude and frequency by 16% and 36%, respectively. Reservoirs in the LMRB have a greater influence during the dry season (Dang et al., 2020; Piman et al., 2013a). It is worth mentioning that recent research (Ji et al., 2018; Wang et al., 2020) based on remote sensing and hydrological modeling pointed out that China's reservoirs have minimal impact on the reduction of the Tonle Sap Lake. Instead, the large-scale construction of dams on downstream tributaries is the significant contributor to hydrological alterations in the Tonle Sap Floodplain (Arias et al., 2014).

In the twenty-first century, climate change and hydropower expansion have brought new challenges to the LMRB. Kiem et al. (2008) and Hoang et al. (2016) pointed out that future increased precipitation will change streamflow patterns and increase flood risks in the LMRB. At the same time, due to the demand for energy, rapid expansion of hydropower will more directly alter river flow. Yang et al., (2019a, 2019b) and Yun et al. (2020) reported that reservoir regulation will reduce streamflow in the wet season and increase streamflow in the dry season in the LMRB. Under the combined impact of future climate change and hydropower development, streamflow and water hazards in LMRB will change drastically.

A large number of studies have evaluated the hydrological impact due to future precipitation and temperature changes under a changing climate. Based on CMIP5 forcing data, Hoang et al. (2016) found that future water vapor content will increase during the wet season (8 out of 10 scenarios) and dry season (all 10 scenarios) in the LMRB. At the same time, the extreme high streamflow of the LMRB in the twenty-first century (Hoang et al., 2019), as well as the magnitude and frequency of floods, will also exhibit a continuously increasing trend (Wang et al., 2017). However, projections of future drought based on GCMs has greater uncertainty. Kiem et al. (2008) projected that drought events would decrease due to increased precipitation, while Thilakarathne and Sridhar (2017) projected that greater interannual variability will exacerbate drought. The evaluation results indicate that future climate change will dominate the annual flow changes, including the increase in average annual flow and inter-annual fluctuations, which can lead to more severe droughts and floods.

Different to climate change, reservoir regulation mainly dominates the change of seasonal runoff, including decreasing intra-annual fluctuations and reducing flood events. Lauri et al. (2012) reported that climate change may exacerbate or offset the wet season flow (−21 to +4%) at Kratie station during 2032–2042. Wang et al. (2017) reported that the reservoirs in the upper LMRB can alleviate the increasing flood risk upstream of Luang Prabang station. At the same time, many GCMs project that streamflow will increase during the dry season (e.g., Hoang et al., 2016). Reservoir operation in the LMRB can also reduce dry/wet hydrological extremes increased by climate change. On the whole, after considering the combined effect of climate change and dams, reservoirs show a strong effect in regulating seasonal streamflow change, including an increase in dry season flow (+150%) and a decrease in wet season flow (−25%), as well as a reduction of flood magnitude (−2.3 to −29.7%) and flood frequency (−8.2 to −74.1%) (Yun et al., 2021a).

7.4.3 *Adaptation and Mitigation of Extreme Events*

Climate change will bring new challenges to water resource management. In the future period, the LMRB will likely encounter more hydrological extreme events (droughts and floods), and reservoirs are regarded as one of the most important measures to deal with future uncertainties. Under the impact of climate change, the LMRB's future extreme events will continue to increase, including more frequent meteorological/hydrological droughts (Sam et al., 2019) and higher flood risks (Hoang et al., 2016; Wang et al., 2017). Based on the latest CMIP6 projections, Yun et al. (2021a) showed a dramatic increase in drought events during the mid-twenty-first century and flood events at the end of the twenty-first century in the LMRB. Recent studies (Guo et al., 2020; Wu et al., 2018) suggest that properly functioning reservoirs can delay the propagation from meteorological extreme events to hydrological extreme events by releasing/storing water in different situations. It is estimated that the LMRB's reservoirs can mitigate the impact of climate change on droughts and floods, reducing most of the basin-wide dry hydrological extremes as well as the 32% of wet hydrological extremes. However, the effect of reservoirs in mitigating long-term extreme events (return periods of more than 6 years) is relatively limited.

The LMRB is one of the basins with the least amount of irrigation water during the dry season (Haddeland et al., 2006). Different from some other basins in the world where reservoir functions are in direct competition, the hydropower generation of the reservoirs in LMRB is complementary to agricultural irrigation (Lacombe

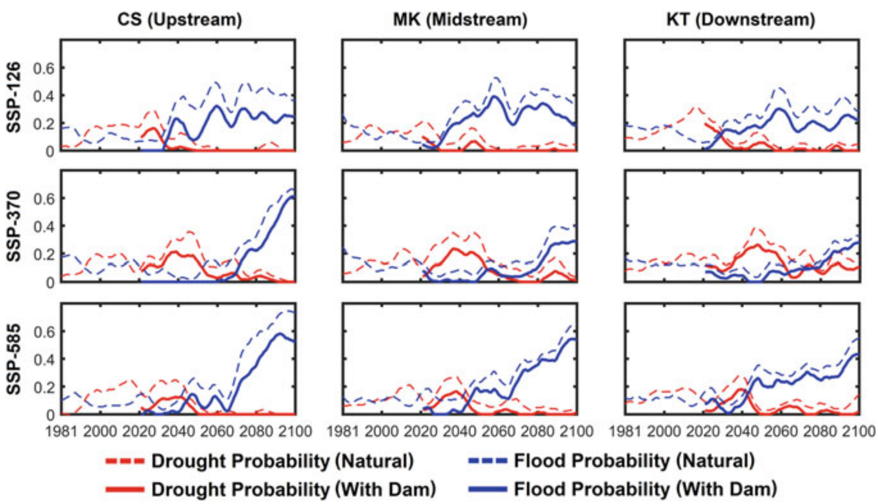

Fig. 7.4 Time series of drought probability and flood probability at the three representative stations during 1981–2100 in LMRB under the impact of climate change and reservoir operation. The probability is calculated from the 30-year moving value (Fig. 7.4 was redrawn according to the data of Yun et al., 2021a)

et al., 2014). Reservoir regulation has increased the dry season flow and reduced the wet season flow in the LMRB. The increased dry season flow will supplement the dry season's irrigation, and the reduction in flood risk caused by decreased wet season flow, will benefit agricultural production (Yun et al., 2020). Under the dry and hot climate conditions in the future, reservoir regulation will reduce the ecological, agricultural and fishery economic losses in the midstream and downstream LMRB (Yang et al., 2019a, 2019b).

With the continuous construction of reservoirs in the LMRB, the riparian countries recognize that a well-established Lancang-Mekong cooperation mechanism will facilitate the deployment and cooperation of transboundary water resources to cope with future drought and flood events (Kittikhoun & Staubli, 2018; Li et al., 2019). For example, emergency releases from upstream reservoirs mitigated severe drought in the downstream countries in March 2016 (Hecht et al., 2019), and this case also confirms that increased dry season flow can alleviate the constraints of salt and acid groundwater on delta agriculture (Piman et al., 2013a; Smajgl et al., 2015). The latest assessment results (Yun et al., 2021b) carried out in the LMRB showed that while climate change would increase flood risk, adaptive reservoir operation can reduce flood magnitude by 5.6–6.4% and frequency by 17.1–18.9% at the cost of 9.8–14.4% of hydropower generation. In particular, upstream reservoirs will suffer more hydropower loss (5.4 times that of downstream reservoirs) to benefit downstream flood control in the LMRB (Yun et al., 2021b).

Reservoir operations established through in-depth international water cooperation can mitigate hydrological extremes in transboundary rivers (Wheeler et al., 2018; Yu et al., 2019). However, reservoir operations that lack international cooperation will prioritize their own water use in upstream countries, for example, reservoir over-discharge during floods or unrestrained water storage during drought, which will exacerbate flood and drought disasters in downstream countries. Existing organizations (such as the Mekong River Commission) and emerging basin-wide organizations (such as the Lancang-Mekong Cooperation) will conduct integrated regulation and cooperation in the LMRB to achieve transboundary management and coordination of water resources. China has shared hydrological data at Jinghong Station (near the China-Myanmar border) since November 2020, which will provide an important basis for supporting LMRB cooperation.

7.5 Conclusion and Recommendation

This chapter comprehensively reviews the characteristics of drought and flood changes during historical and future periods in the LMRB under the impact of climate change and human intervention.

In the past decades, there were obvious spatial distribution patterns of drought in the LMRB. Drought has increased significantly over the middle and the lower LMRB during 1979–2019. Similarly, floods have obvious temporal and spatial distribution patterns affected by topography and precipitation. The further downstream, the later the rainstorms end, and the later the flood season ends. Floods mainly occur in July–October, with the highest probability of flooding in August, and the flood peak values downstream are much higher than those upstream. Floods are now one of the most threatening hazards in the LMRB.

With future climate change-induced increases in temperature and precipitation, results based on GCMs and hydrological models showed that the annual flow will increase but the flow in dry season will decrease, it is estimated that the LMRB will face a severe drought threat during the mid-twenty-first century. Meanwhile, climate model projections indicate that the flood frequency will increase by 10–140%, the flood magnitude will increase by 5–55%, and the peak inundation will enlarge by 19–43% in the twenty-first century. This will potentially cause economic losses and human fatalities. The basin-wide adaptive strategies including flood forecasting and enacting new flood protection standards are therefore urgently need to be planned and carried out.

To tackle the increasing future droughts and floods, reservoirs in the LMRB have expanded at unprecedented rate over the past twenty years. By 2021, the total storage capacity of the 103 huge reservoirs in the LMRB reached a staggering 100.3 km^3, accounting for 23% of the annual flow. These reservoirs are regarded as one of the most important measures to mitigate future extreme events. Reservoirs show an effective regulating effect for streamflow and extreme events, including an increase in dry season flow and a decrease in wet season flow, as well as the reduction of future droughts and floods.

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Chapter 8
Integrated River Basin Management

Shaofeng Jia, Aifeng Lyu, Wenbin Zhu, and Boris Gojenko

Abstract Integrated River Basin Management (IRBM) involves the integration of the multiple uses of water, the integration of multiple properties of water: water disaster, water resources, waterways, water environment, water ecology, water landscape and water culture, and the integration of water by space: upstream vs downstream, left bank vs right bank. The main problems of IRBM within the Lancang-Mekong River Basin includes flood disaster, navigation and its impact to basin cooperation, contradiction between development and protection, and public security in a framework of cooperation and integration. It has been a general concern for Mekong countries to manage water conservancy engineering and coordinate water supply, navigation, fishery, power generation, and water disaster management. All stakeholders put great emphasis on water conservancy engineering management in terms of basin planning, domestic and cross-border project construction, and cooperation mechanisms. In order to ensure the sustainable use of water resources, a series of continuously updated plans were proposed. Those plans set goals and provided measures for the rational and sustainable development of the resources in the basin, and meanwhile, it also put forward a mechanism to offset the adverse effects. The development of international navigation has deepened win-win cooperation, strengthened regional economic exchanges and tourism development, promoted regional prosperity among China, Laos, Myanmar and Thailand. The basin has abundant fishery resources and has the world's third most diverse fish population, with 1,148 fish species, after the Amazon and Congo River Basins. Mekong countries

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have different needs for the development of fishery resources due to their different geographical locations and economic development, and thus very little cooperation in fisheries has been carried out among Mekong countries. The basin's ecohydrological management involves environmental flow, water quality, soil erosion and sedimentation, aquatic organism and underground water protection. The current measures include enhancing monitoring, scientific assessment, rational regulation of water system, the establishment of natural reserves, and international cooperation. Climate change and construction of dams are both critical challenges faced by the basin in terms of ecohydrological management in the 21st century.

8.1 Introduction [Shaofeng Jia, Boris Gojenko]

8.1.1 Definition of Integrated River Basin Management

The most broadly definition of integrated water resources management (IWRM) is by the Global Water Partnership: "A process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000). The most common approach is to consider the river basin as an integrated ecological system that includes natural resources and other components of the environment, along with anthropogenic inputs of labour, capital and materials (Hooper, 2005).

In water resources management, the basin is considered as an independent hydrological unit and remains the most effective unit for planning and implementation of IWRM (Jones et al., 2006). Hence, integrated river basin management (IRBM) is a more accurate term while we speak about the IWRM limited by frames of a basin. Further, in this case the water resources management is supposed to be more effective and water use more accountable. Following the IWRM definition by GWP (2000), the IRBM is defined as: "The process of coordinating conservation, management and development of water, land and related resources across sectors within a given river basin, in order to maximise the economic and social benefits derived from water resources in an equitable manner while preserving and, where necessary, restoring freshwater ecosystems" (WWF, 2002).

8.1.2 Aspects of IRBM

8.1.2.1 Integration of Multi-purpose Use of Water

For many countries, especially at the stage of their active economic development, multipurposes of IRBM includes many elements, such as use of water for irrigation, municipal and industrial water supply and sanitation; power generation at hydroelectric power plants; navigation and transport; and much more (Worki, 1971). All this undoubtedly requires huge volumes of water. At the same time, it is necessary to maintain a strict balance between all water users.

The modern multifunctional dams are one of the best examples of such management. Firstly, they are called to store water for agricultural, municipal and industrial water use. Secondly, they have a potential to produce environmentally friendly electricity. Thirdly, the cascades of reservoirs regulate the water flow, which makes it possible to avoid floods and droughts since it accumulates a certain volume of water. Fourthly, the water area of the reservoirs is an ecosystem for a number of flora and fauna. Fifth, reservoirs create conditions for social events, for example, tourism, fishery, fishing, hunting, etc. (Branche, 2015).

8.1.2.2 Integration of Multi Properties of Water: Disaster, Resources, Waterway, Environment, Ecology, Landscape and Culture

In order to effectively manage water at the basin level, it is very important to take into account all its properties, and not only positive, but also negative aspects. Accordingly, the positive properties should be improved and multiplied, and the negative ones should be fought and overcome.

When any natural disasters appear, most often it is associated with water in one form or another. Floods, droughts, landslides, avalanches, storms have been increasing and becoming more frequent lately. Water-related disasters have both direct impacts (damage to buildings, crops and infrastructure, loss of life and property) and indirect (reduced productivity and livelihoods, increased investment risk and health impacts). Rising economic and disaster costs should provide a significant incentive for riparian states' governments to pay more attention to preparedness, prevention and tackling the root causes of vulnerability (UN Water, 2020).

The desire of many countries (especially developing ones) is to manage water as resource to meet the needs of their populations. In this view, the IRBM aims to propose an environmentally sustainable water management approach in which human water needs are met in a way that maintains or restores the ecological integrity of the affected river ecosystems.

The development of waterways is also one of the most important components of IRBM. Apart from their traditional role as a system of travel or transport they serve a variety of functions such as: water supply, transfer and drainage; tourism, sport, cultural leisure and recreational; heritage landscape, open space and ecological services. In other words, waterways act as an agent or catalyst for ecological and social rural and urban areas (British Waterways, 2003).

Water and land use and development can harm water resources if not carefully planned and managed. Therefore, IRBM should aim to integrate water and land use planning in such a way as to support the economic growth of the population and the development of the state, meet environmental needs and ensure a balance of economic, social and cultural benefits.

Changing climatic and water conditions and the increasingly dry conditions have made water conservation a priority for many countries. Landscape professionals can implement simple and smart water saving strategies that will become part of the solution. Appropriate cultural practices are an essential component of efficient water use and management in urban and rural landscapes, reducing waste and maximising the health of landscapes (Wallace & Siegel-Miles, 2017).

Further, forests, grasslands, agricultural land and water resources are closely related. All these issues have been discussed for a long time in isolation from each other. However, in recent years, this connection has been growing and has attracted the attention of experts in the fields of forestry, agriculture, water resources management, landscape conservation and environmental issues. There is an increasing need for different sectors of the economy and countries to communicate and collaborate with each other to facilitate coordination and alignment of plans and instruments, especially in the light of climate change.

For example, in the area of water and forest nexus, there are great opportunities for joint activities that can benefit both forests and water resources. As a result of effective IRBM, forests make the most significant contribution to ensuring water availability. Forests minimise erosion and thus reduce the damage to water quality due to siltation through stabilising the soil. In addition, by trapping sediment and pollutants from other land uses and slope activities, forests can protect water bodies and streams (FAO, 2009).

8.1.2.3 Integration by Space: Upstream Versus Downstream, Left Bank Versus Right Bank

It is well known that water use and water consumption in upstream countries can substantially affect the economic, social and environmental situation of downstream countries. Moreover, it does not matter how far these countries are from each other—a few kilometers or several hundred kilometers (Rasul, 2014). There are also cases in the world when the well-being of not one, but several downstream countries, and even the entire region as a whole, depends on water use of the upstream country: for example, Amu Darya, Mekong, Nile rivers.

Nepal et al. (2014) classifies the causes of the impact of the upstream country water use on the downstream country into two types: (i) anthropogenic impacts in the form of land use and (ii) natural impacts in the form of a changing climate. Both types of these causes invariably lead to changes in the hydrological regime, which can lead to irreversible consequences.

Undoubtedly, the inappropriate water use by upstream countries can have a negative impact on the statement of downstream countries. Conversely, the careful and wise use of water resources upstream contributes to development of downstream countries and the entire basin region. This raises the dependency ratio of downstream countries (Dukhovny & De Schutter, 2018).

Some literature also contains descriptions of how downstream countries' activities influence the development of upstream countries. For example, as the downstream countries are located closer to the sea, development of navigation in these countries is helpful to economic development (trade, food delivery, etc.) and social development (transport, tourism, etc.) in upstream countries (Barret, 1994). Another example is the development of fisheries in the lower reaches, where the fish leave for spawning in the countries of the upper reaches of some rivers. In these two cases the situation opposite to upstream–downstream influence is observed—where upstream countries become dependent on downstream countries (Moellenkamp, 2007).

There is one more spatial dimension that requires the obligatory resolution of water disputes: between countries on different banks of the river. Scientists believe that in this case, the country's activities on the right bank may affect the country's activities on the left bank (and vice versa). For the most part, the literature provides two main factors of impact on water resources in this approach: environmental problems and navigation problems, which ultimately can lead to social and economic losses. If a system of joint coordinated actions is introduced, they will entail the same common benefits (ADB, 2013).

With regard to navigation, a joint approach, research and work in the field of maintaining the bottom and banks of the river in a normal functioning state is needed here. For example, it is necessary to take measures to clean the bottom and river banks from sediment, prevent the formation of river islands, joint works to recover from natural disasters, etc. (Wood, 1999).

Taking into account the long tradition of water cooperation on the basin levels, it can be concluded that understanding and considering all of the above circumstances is a prerequisite for IRBM which should be based on:

- joint social approaches: green tourism, fish farming and fishing, etc.;
- joint ecological approaches: obligations on environmental flow, soil erosion control, non-pollution of waters and observance of supervision over water quality; unimpeded passage of fish for spawning, etc.,
- joint economic approaches: development of navigation, payments for ecosystems services, penalties and compensation for water pollution, etc.
- joint political and institutional approaches: joint management of water and other natural resources and mutual decision-making together with broad stakeholder involvement for basin planning.

8.1.3 Main Problems of IRBM Within the Lancang-Mekong River Basin

8.1.3.1 Flood and Drought

Influenced by distinct wet and dry climate, climate change and El Nino, floods or droughts of varying degrees frequently happened in the basin (Chen et al., 2020). Since the 1980s, the drought and flood disasters have occurred frequently in the basin due to the interaction of multiple monsoon systems (Hundertmark, 2010).

Between 1970 and 2017, 225 flood disasters occurred in the basin that led to almost 12,000 deaths, over 100 million lives disrupted and more than 50 billion USD in economic damages (CRED, 2017). The more hazardous flood disasters in recent decades include the 2000–2001 and 2011 Mekong Delta floods, the 2011 Central Thailand floods and the 2015 Myanmar floods. Climate change is expected to further increase the frequency and intensity of floods in the region in the coming decades (IPCC, 2012).

In terms of flood risk, it can be noted that the highest risk of flooding in the basin is observed in Cambodia and Vietnam, a high risk in Laos, and medium risk is in Thailand (Sok, 2013).

Floods, on the one hand, cause huge financial losses. Such losses in 2012 amounted to 61 million USD (MRC, 2013a, 2013b). Estimating form the data of Chen et al. (2019), from 2000 to 2017, the average flood fatalities in the riparian 5 countries except China was 253.5 person/a and showed an increase trend. On the other hand, they can be beneficial. The benefits of flooding include maintaining annual fish yields, especially in the Great Lake, maintaining 5.24 million hectares of flooded wetlands in the lower Mekong with associated socio-economic benefits, providing water for irrigation during dry seasons, fertilizing floodplains with annual silt deposition, etc. (MRC, 2013a, 2013b).

Following the MRC (2010b), the average annual direct cost of flooding to agriculture, infrastructure, and buildings in the lower Mekong is 60–70 million USD a year. Where Cambodia and Vietnam account for two-thirds of the total. In turn, the average annual value of flood benefits is 8–10 billion USD, i.e. about 100 times the cost. The challenge for better flood risk management is to reduce the costs and impacts of flooding while preserving the benefits (ADB, 2008).

Following the devastating floods of 2000–2001, the basin member countries have taken decisive steps to combat floods. The aim of these activities was to reduce the damage to infrastructure, economic losses, loss of life among the population, and their livelihoods as a result of extreme floods (Hoang et al., 2018).

The Flood Management and Mitigation Strategy was developed and implemented, followed by the development and implementation of a special Flood Management and Mitigation Program (FMMP) in 2004. The FMMP was developed as an integrated programme, consisting of the following components: (i) Establishment of the Regional Flood Management and Mitigation Center; (ii) Structural Measures and Flood Proofing; (iii) Enhancing Cooperation in Addressing Trans-boundary Flood Issues (iv) Flood Emergency Management Strengthening; and (v) Land Management (Sok, 2013).

In addition to natural causes of floods in the basin, there are also anthropogenic ones. Among them is the widespread construction and use of hydro-electricity plants (HEPs). In order to generate electricity on HEPs, it is necessary to discharge water mainly during winter periods, which entails a change in the flow regime of the river. And the sudden start of the hydropower station and the sudden release of water from the dam cause the downstream river to rise sharply, which may cause flood losses. The situation is aggravated by climate change and the region's susceptibility to these changes. For example, in 2019, the issue of floods was at the head of the annual report of the Mekong River Commission (MRC, 2020). On the other hand, the dams of HEPs are designed to regulate the river flow, which in the future will allow avoiding, or at least minimizing the risk of floods.

According to Chen et al. (2019), from 1900 to 2017, the total death toll of flood, storm and drought was respectively 12,941, 165,830 and 0 person, the total injury toll was 5742, 33,594 and 0 person, the total economic loss was 52.99, 15.29 and 11.26 billion US$. The water-related 3 disasters took up 93% death toll and 98% economic loss of all natural disasters.

For better responding to flood and drought, in addition to hydrological data, other information has been shared among the basin states. A mechanism of data and information sharing on floods, droughts and emergency water-related situations is under continuous consideration and discussion among basin member countries (LMC, 2018).

In order to help downstream countries with flood control and drought resistance, the Ministry of Water Resources of China started to officially provide the whole year of hydrological information of the Lancang River and Mekong River countries from November 1, 2020 (MWR, 2020).

8.1.3.2 Navigation Problem and Its Impact to Basin Cooperation

The other most pressing issue for IRBM in the basin is navigation development and its hidden benefits. Waterfalls and dangerous shoals have greatly hindered the development of river navigation. Which in turn through its capacity influence on trade and thus on social and economic development of the entire basin region of.

The most significant event in this direction took place in June 2001. The Chinese government signed an Agreement with Thailand, Myanmar and Laos to improve river navigation. Remarkably, this agreement was the first time the authorities of China and Myanmar were involved in any agreement on use of the Mekong River waters. As part of this agreement, China received the right to clean 33 km of the Mekong River. The ultimate goal of this event was to allow commercial up to 150 tonnes vessels from China (Yunnan Province) to Luang Prabang (Osborne, 2019). This route is restricted for large vessels due to obstacles on the river. Huge investments for the development of cross-border river trade have already been completed in the Chinese territory. Extensive dredging of the river was carried out and ports were built at Simao and Jinghong, as well as on the China-Laos border at Guanlei. For China, this agreement marks an important event called the "Opening of the South Gate". This implies a policy of expanding economic ties with the countries of the mainland of Southeast Asia (Ratner, 2003).

Thailand's interest in this agreement is mainly of an economic nature. This would provide a direct trade route to China, which could give a competitive edge over other countries using the congested ports of the South China Sea (Goh, 2004).

The prospect of expanding economic and trade ties through the development of navigation has great implications for political and social relations between downstream and upstream Mekong river countries. On this base, China has established a research group at the state level to develop and plan development cooperation with other basin countries.

8.1.3.3 Contradiction Between Development and Protection

There is no doubt that any development requires certain sacrifices in the short term. But mutual agreement will give undeniable development results in the long term. Therefore, development often requires some concessions in protection.

The river basin provides a huge potential for cooperation in view of HEPs construction and electricity generation. Most of the existing HEPs as well as those under construction are located in China. The construction and use of HEPs is extremely important for the region. For China, this is an opportunity to cover the needs of its large population in electricity at the expense of cheap and environmentally friendly energy. For Laos, it is an opportunity to achieve the title of "Battery of Southeast Asia", to develop its exports, and thereby improve its economic situation and eradicate the poverty of its population (OECD et al., 2020).

During the construction of HEPs large areas are flooded, and people are sometimes relocated far from their original homes. There were even cases where people's costs from forced resettlement in Laos was not recompensed (Belay et al., 2010). Moreover, not only settlements are flooded, but also agricultural lands. The appropriate protection of people is needed in order to regulate the development of the country.

In addition to the problems associated with the construction and operation of HEPs, the basin has a number of other factors that negatively affect it. This includes over-intake water for irrigation in Thailand during dry seasons, such as observed in 2016. This caused damage to the Mekong delta in Vietnam. This, along with the constant discharge of drainage water from agricultural fields, wastewater discharge from industrial and municipal enterprises, as well as mining, already leaded to water pollution and environmental problems, especially in the downstream of the river (Xing, 2017).

As described above, river shoals have greatly hindered the development of river navigation and this in turn is a cause of conflict between China's desire to use the Mekong as a transport corridor and Thai activists desire to maintain the environment. In order to start up heavy vessels on the river, China needs to carry out dredging works. Thai environmentalists are against this, because they fear that these procedures may harm the fragile ecology of the Mekong in their territory (Ratner, 2003).

The uncontrolled extraction of sand and gravel from the river bed for construction purposes in Vietnam leads to erosion and the collapse of river banks, as well as the release of suspended particles into the water and hence sediment deposition in the Mekong delta.

All described problems are still existing in LMRB. But again, in order to achieve the economic development success, many difficulties must be overcome.

8.1.3.4 Public Security in Frame of Cooperation and Integration

Despite the pace and levels of modern development, there are a number of obstacles to its successful implementation. One of these barriers is security. The description of this problem begins with a negative example on the Mekong River.

In October 2011, the Chinese river vessels Heping and Yuxing-8 were attacked on the Mekong River. The attack took place in the Golden Triangle, where the borders of Myanmar, Laos and Thailand converge.

Soon after the seizure of vessels, the bandits were attacked by the Thai military, who recaptured vessels. At the end of the military operation, large consignments of drugs were found on the sides of both vessels, which the bandits planned to transport downstream of the Mekong.

According to the Thai military, the Nor Kham group, including more than 400 militants in its ranks, attacked Chinese ships and destroyed their crews because the Chinese refused to pay the gang for protection. Vessels in turn were hijacked to transport drugs from Myanmar to Thailand. In the past, the group has tried to levy payments from Chinese vessels on the Mekong River.

The incident led to the organisation in Beijing by ministerial representatives of China, Laos, Myanmar and Thailand of joint patrols on the Mekong River. There, it was decided that from the end of 2011, the four countries would begin joint patrols on the Mekong River.

At the meeting, it was agreed that a headquarters would be set up in China to manage joint patrols on the Mekong River, and points of contact would be set up in the other three countries. The concerned authorities of these countries would be provided with a round-the-clock information channel. In addition, China pledged to provide Laos and Myanmar with the necessary patrol equipment and training support (Shabalina, 2012).

Cross-border criminal economies often develop in parallel with the integration of legitimate economies between countries. For centuries, there have been opportunities and channels for the trade of illegal goods across borders in East Asia and elsewhere.

Unfortunately, the opening of borders between partner countries, the organisation of economic and transport corridors, the opening of transnational trade river, land and railways entails the activation of transnational criminal supply chains (Luong, 2020). This requires consideration of safeguards and careful training of public security agencies.

The Mekong River has always been an important channel for people and goods between the many cities along its banks. The traditional forms of small craft trade that bind communities continues today. But the river is also becoming an important link in international trade routes.

Likewise, the social, economic and developmental importance of the Mekong River also creates opportunities for criminal activity to flourish. Improvements in infrastructure have exacerbated criminal threats to prosperity and peace, and many types of organised crime are expected to benefit from easier access and wading through the Mekong. Trafficking in drugs and precursors is a key problem that needs to be addressed. Recognising this, the basin states signed the Memorandum of Understanding (MOU) on Drug Control, together with UNODC, as key to illicit drug production and trafficking (UNODC, 2016).

Moreover, realising the seriousness of the problem in October 2015, the Ministerial Meeting on Law Enforcement and Security Cooperation along the Mekong River was held in Beijing and the Joint Statement on Strengthening Cooperation on Law Enforcement and Security Cooperation along the Mekong River was approved.

This joint statement comprehensively addresses security cooperation along the Mekong River in the LMRB countries; methods of combating crime, drug trafficking, terrorism, cybercrime; key areas of cooperation and the fight against smuggling, illegal migration and the detention and repatriation of criminals (Lu, 2016).

As has been repeatedly described in various sources, water is an essential resource that plays a special role in sustainable development of every nation. Public security is a prime concern in every country in the world. And in transboundary river basins such as the LMRB, it largely depends on international cooperation between countries.

Despite this, it was China that initiated the Lancang-Mekong Cooperation Mechanism, which improves political and economic ties in the basin. Both of these formats of riparian relations will be discussed in detail in subsequent chapters.

8.2 Water Conservancy Engineering Management

Before the 1980s, the Lancang-Mekong water resources were mainly developed and utilised for agricultural irrigation, navigation, and fishery. With the development of society and economy, more attention has been paid to the abundant hydropower resources of the Lancang-Mekong River. As a result, hydropower development and the various flood control and drought-resistant projects have become the focus of development and utilization. It has been a general concern for Mekong countries to manage water conservancy engineering and coordinate water supply, navigation, fishery, power generation, and water disaster management. Therefore, all stakeholders put great emphasis on water conservancy engineering management in terms of basin planning, domestic and cross-border project construction, and cooperation mechanisms. The hydropower development and the flood control and drought relief projects have been introduced in the previous chapters, so this chapter focuses on the aspects of water resources utilisation, navigation, and fishery.

8.2.1 Water Resources Utilisation

8.2.1.1 Status Quo of Water Resources Utilisation of the Lancang-Mekong River

The countries that the Lancang-Mekong River flows through have different social development and economic systems. The utilisation of water in these countries mainly includes domestic water use, agricultural irrigation, hydropower, and waterway transportation, among which agricultural irrigation results in the most loss and consumption of water in the basin (Wen, 2016). Currently, the Lancang-Mekong countries have different development and utilisation status of water resources, which is described as below.

Since the 1990s, the Chinese government has attached great importance to the development of the Lancang River. The economic benefits brought by its development are not only conducive to the harmony and stability of ethnic minorities in the frontier areas but also influential to the lower reaches. The Lancang River Basin has many mountains and canyons, which are not suitable for agricultural development and farming. As a result, agricultural irrigation only accounts for minor use of water resources. On the other hand, the development of hydropower, shipping, and tourism requires high water use intensity (Wen, 2016).

In Laos, agriculture plays a dominant role in its economic structure, accounting for two-thirds of its annual GDP. The country is highly dependent on the Mekong River since agriculture feeds nearly 75% of its population, and the Mekong River provides water for about 60,000 hm^2 of land (Liu, 2013). At present, Laos hopes to promote its farm economy by developing and utilising the water of the Mekong River while developing irrigation and water conservancy to push agricultural development. In Myanmar, the Mekong River only flows through a small part of the country. The water development issues related to agricultural irrigation and hydropower are relatively insignificant, and thus apart from a few small-scale agricultural irrigation projects, it has low participation in the water development in the basin. Its primary concern lies in the development and protection of its forest vegetation (Liu, 2013).

Compared with countries dependent on agricultural development, Thailand's economic structure is relatively diversified. Although the development of agriculture only accounts for about 20% of Thailand's GDP, the export of agricultural products makes up a high proportion of around 60% of the total, and farming provides 70% of job opportunities in Thailand. However, since Thailand has continued its extensive use of the traditional slash-and-burn, many problems have emerged, including a significant reduction in forest area, severe soil erosion, decreased irrigation efficiency, land salinisation, uneven distribution of water resources, etc. Thailand mainly hopes to use the water of the Mekong River to irrigate the largest arid area in the northeast of the country and expand the irrigation area by the "Northern Mekong-Loei-Chi-Mun River Management and Artesian Water Diversion" project (Qi & Long, 2011). Thailand also wants to promote the regional economy by developing agriculture, so the Mekong River is of great significance to Thailand's economic and social development.

More than 85% of Cambodia's territory lies in the Mekong River basin. In 1993, agricultural output accounted for about 50% of Cambodia's gross national product (GNP), and about 80–85% of the labour force was engaged in agricultural production. The development and utilisation of the water resources of the Mekong River in the Cambodian basin, including the largest freshwater lake in Southeast Asia-Tonle Sap Lake (also known as the Great Lake), and the irrigation of agriculture, are irreplaceable for Cambodia's economic and social development. Cambodia's primary demand is that the Mekong River's upper reaches would collect a considerable amount of floodwater during the rainy season to ensure the fertility of the soil in the floodplain of the Tonle Sap Lake. Therefore, Cambodia opposed the plan that Thailand diverts water from the Mekong River to increase its irrigation in the low water season because it affects the lower Mekong countries' water volume (Zhao et al., 2017).

Vietnam is also on the opposing side. Among the four member states of the Mekong River Commission (MRC), Vietnam has the largest area to be irrigated, and it also has the highest dependence on agriculture. The use of water in Vietnam heavily relies on the volume of water in the upper reaches. Therefore, Vietnam hopes that the development and utilisation of water in the Mekong River can ensure its agricultural irrigation, prevent seawater intrusion, and protect its ecological environment. The water intake and storage project on the upper mainstream will impact the natural flow of the Mekong River, especially in the dry season. If the upstream water continues to decrease and the water level continues to drop, there will be an increase in the possibility of a drought delta and seawater inflow. Large-scale seawater intrusion will lead to salinisation of the fertile farmland in the area. Therefore, Vietnam strongly opposes the construction of dams and consequent diversion of water in the mainstream of the Mekong River.

8.2.1.2 Water Resources Management Policy of the Mekong River

In recent years, Mekong countries have continued to accelerate the Mekong River's development of water resources at different levels. Due to the water's cross-border mobility, lower Mekong countries have realised the economic potential of Mekong water resources in promoting economic growth, reducing poverty, and creating job opportunities. However, without proper planning and management, its rapid development will have a negative impact on the health of the river, resulting in increased pollution, floodplain changes, and habitat destruction. In order to ensure the sustainable use of water resources, a plan for the Lower Mekong River Basin was proposed. This plan set goals and provided measures for the optimal and sustainable development of the resources in the basin, and meanwhile, it also put forward a mechanism to offset the adverse effects.

The plan for LMB can be traced back to 1957, when Laos, Thailand, Cambodia, and South Vietnam formed the Committee for Coordination of Investigations of the Lower Mekong Basin. The initial cooperation focused extensively on data collection and carrying out research on agriculture, fishery, navigation, and education. In

1970, the MRC formulated the Indicative Basin Plan (IBP) and proposed a 30-year development plan that included the expansion of irrigation, navigation, hydropower, and flood control infrastructure. Later in 1987, the MRC cut the plan to twenty-nine projects. However, due to regional military conflicts, most of the projects have not been implemented. With the continuous increase of investment in water infrastructure projects, people have recognised the strong impact of the Mekong River's water resources on society and the environment. Therefore, the four lower Mekong countries (Cambodia, Laos, Thailand, and Vietnam) reached an agreement on cooperation for sustainable development for the Mekong River Basin, which facilitated the establishment of the MRC and opened a new era for taking coordinated approaches to the planning of the LMB. Based on the 1995 Mekong Agreement, the MRC served as the coordination center for cooperation, provided shared information and technical guidance, and assisted member countries in achieving their basins' goals. The MRC was also required to formulate a basin development plan to classify the basin's first-level projects and programs. Consequently, it established a Basin Development Plan (BDP), focusing on developing principles, tools, research, and strategic directions. The plan was divided into two phases. From 2001 to 2006, the first phase (BDP1) laid the foundation for cooperative planning, bringing four member states together to build relationships, and developed planning processes, assessment tools, and knowledge bases. From 2007 to 2010, the second phase (BDP2) was implemented, but there was increasing pressure on the development of water resources in the basin during this process. After recognising the limitations of the data and the knowledge, BDP2 focused on transnational water issues to eliminate the long-term obstacles that affect the Mekong River Basin's sustainable development. By 2010, BDP2 had provided sufficient data and information for member states to develop and evaluate their interests, development plans, and positions related to water resources. The assessment of the whole basin's prospects in BDP2 was used to formulate a basin development strategy (BDS). The strategy, which was based on the integrated water resources management mechanism, further promoted cooperation among member states to ensure the Mekong River's sustainable development and management. The emergence of the first BDS between 2011 and 2015 has become an essential milestone in the history of Mekong cooperation. The MRC shifted its focus from acquiring water management knowledge and the best practices to focusing on how the Mekong countries share, use, and manage the resources to sustain the Mekong River's economic growth. During the third phase of BDP (BDP3), the MRC started to draft a status report and supported the implementation of MRC procedures. The "2016–2020 River Basin Development Strategy" continues to address the first BDS priorities, focusing on the sustainable development of the LMB and the management of plans and projects brought up by various countries (https://www.mrcmekong.org/our-work/functions/basin-planning/). The "2016–2020 River Basin Development Strategy" elaborated on implementing the updated Mekong River Basin development strategy based on integrated water resources management by the MRC at the regional level. It also presented the institutional reform measures brought up by the MRC in the decentralisation roadmap. The strategy guided the Mekong River Commission Secretariat (MRCS) to support the MRC member countries to promote and coordinate the sustainable development of the Mekong River Basin in the next five years, and also pointed out the direction of cooperation among the MRC, the implementing agencies of member countries, the dialogue partners (China and Myanmar), the development partners and the stakeholders on a larger scale (MRC, 2016). In order to better promote and coordinate the sustainable management and development of water and other related resources in the LMB, the MRC launched the 2021–2030 Basin Development Strategy (BDS) and the 2021–2025 MRC Strategic Plan (SP) in April 2021 (MRC, 2021).

In addition, each country is carrying out integrated water resources management based on their conditions. With more complete systems and management frameworks, each country will explain its national water policies and strategies and define the responsibilities for water resources management in a more precise way. All LMB countries now have a dedicated agency responsible for water resources management. These agencies establish river basin organisations and carry out water management in a participatory approach at the sub-basin level. Water resources management should be further strengthened between and within the Mekong countries.

8.2.2 Waterway Navigation

8.2.2.1 Development of International Navigation

China, Laos, Myanmar, and Thailand have paid close attention to the Lancang-Mekong River Basin since the 1990s. The governments of China and Laos signed an agreement to jointly investigate and develop Mekong international navigation in 1989, which marked the official start of developing Lancang-Mekong international navigation. In May and October 1990, experts from China and Laos inspected the 701-km channel from Jinghong to Luang Prabang and the 1,177-km channel from Jinghong to Vientiane, the capital of Laos. Based on extensive investigation, China and Laos carried out the cross-border shipping trial in 1991. Later from January to May in 1993, China, Laos, Myanmar, and Thailand jointly inspected the boundary pile No. 234 between China and Myanmar—the 361-km section in Bankelong, Thailand, and gave a inspection report on Mekong navigation (Wang, 2001). At the same time, China approved Simao Port and Jinghong Port as national first-class ports (Zhao, 2019). China and Laos signed the “Agreement on Passenger and Cargo Shipment on the Lancang-Mekong River” in 1994, and later China and Myanmar also signed the agreement in 1997. In 1995, the “Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin” between Laos and Thailand provided theoretical and political basis for the development of container traffic in the Lancang-Mekong River Basin. In 2000, China, Laos, Myanmar, and Thailand signed the “Agreement on Commercial Navigation on the Lancang-Mekong River” and carried out cross-border shipping trials, with volume increasing from 500 tons per year to 200,000 tons per year. Based on the agreement, the four countries signed the “Memorandum of Understanding of the Implementation of the Quadripartite

Agreement on Commercial Navigation on the Lancang-Mekong River", formulated eight technical supporting rules, including the "Guidelines on the Maintenance and Improvement of the Navigability of the Lancang-Mekong River", and established the Joint Committee on Coordination of Commercial Navigation on the Lancang-Mekong River. Myanmar also opened Sole Port in 2001. The official navigation of the Lancang-Mekong River marks the official entry of international shipping into the fast lane of development (Li & Xiao, 2019).

With the success of the maiden voyage on the Lancang-Mekong River, China, Laos, Myanmar, and Thailand formally opened channels for navigation in 2001. From 2002 to 2004, the four countries jointly improved the upper Mekong waterway, making sure the upper Mekong basin was navigable all year around. The improvement also promoted the rapid growth of transnational traffic and guaranteed the safe transportation of 200–300 t cargo ships. In Laos, a natural waterway with a total length of about 300 km from Houayxay to Luang Prabang and a river channel of about 459 km from Vientiane to Savannakhet were built, and the channel from Luang Prabang to Vientiane was approximately 476 km long. In 2002, Thailand opened the Chiang Saen Port, and the total volume of cargo in and out reached 500,000 tons per year. The construction of the class V waterway of the Lancang River was completed in 2006. Later in 2007, the Lancang-Mekong international navigation was open all year around, with an annual shipping volume of over 396,000 tons, which marked a relatively complete shipping system of Lancang-Mekong River. In 2011, China, Laos, Myanmar, and Thailand held the 10th Meeting of the Joint Committee on Coordination of Commercial Navigation on Lancang-Mekong River and discussed the maintenance and improvement of the waterway, the navigation safety, and the implementation of the "Charge Rules". In 2012, Myanmar carried out the construction of a 31-km class V waterway on the Lancang River at the China-Myanmar boundary. Myanmar set up a company with overseas partners to open up the shipping market in 2013. In 2015, Laos built power stations, including the Nam Mae Lai hydro-power station Unit 2, to generate electricity. Later in the same year, China, Laos, Myanmar, and Thailand passed the "Development Plan of International Navigation on the Lancang-Mekong River (2015–2025)", which aimed to enhance the overall shipping capacity through cooperation. In 2018, Thailand opened the channel for transporting frozen goods from Guanlei Port to the new Chiang Saen Port, and in the same year, the overall planning and design of waterway transportation in the Mekong River Basin was completed. The development of navigation has deepened win–win cooperation, strengthened regional economic exchanges and tourism development, promoted regional prosperity, and increased the number of ships, the types of cargo, and the total volume of foreign trade among China, Laos, Myanmar and Thailand. The comprehensive utilisation of water resources has brought benefits to the countries and improved regional transportation networks in South Asia and Southeast Asia.

8.2.2.2 Coordination Mechanism of Lancang-Mekong International Navigation

Cambodia, Laos, Vietnam, and Thailand signed the "Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin" and established unified coordination and comprehensive management agency—MRCon April 5, 1995. Later, in 1996, China and Myanmar became dialogue partners of the MRC, and the MRC was the only water resources management organisation that China participated in then. As a dialogue partner of the MRC, China has extensively exchanged experience, planned technical training, and organised field visits with member countries (Hao, 2018). The MRC has already become an agency for regional cooperation and international coordination for 12 development projects in the Lower Mekong River Basin, including water resources utilisation, hydropower development, agricultural irrigation, and navigation. Article 9 of the "Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin" grants the freedom of navigation on the mainstream of the Mekong River and stipulates that "on the basis of equality of right, freedom of navigation shall be accorded throughout the mainstream of the Mekong River without regard to the territorial boundaries, for transportation and communication to promote regional cooperation and to satisfactorily implement projects." In order to promote the development of navigation on the mainstream of the Mekong River, the MRC issued the "Navigation Strategy" in 2003, the "Navigation Programme (NAP) 2013–2015" in 2012, and the first "Dangerous Goods Management Manual (DGGM)" in 2013 (Li, 2017).

To promote the development of international navigation in the LMB, the member states of the MRC have signed a series of bilateral and multilateral agreements, including the "Hanoi Agreement between Cambodia and Viet Nam on Waterway Transportation" on December 13, 1998, the "Agreement among the Lao PDR, Thailand and Viet Nam for Facilitation of Cross-Border Transport of Goods and People" on November 26, 1999, "Phnom Penh Agreement between Cambodia and Vietnam on the Transit of Goods" on September 7, 2000, and the "New Agreement on Waterway Transportation between Vietnam and Cambodia" on December 17, 2009. Although China is not a member of the MRC, it has also actively participated in and promoted the development and cooperation of international navigation on the Mekong River. The agreements it has signed with Mekong countries include the "Agreement between China and Lao PDR on Freight and Passenger Transport along the Lancang-Mekong River" in November 1994 and the "Agreement on Commercial Navigation on the Lancang–Mekong River among the governments of China, Laos, Myanmar and Thailand" on April 20, 2000. China, Laos, Myanmar and Thailand also agreed to establish the Joint Committee on Coordination of Commercial Navigation on Lancang-Mekong River to negotiate and resolve international navigation issues (Chen & Liao, 2008). In November 2014, China, Laos, Myanmar, and Thailand polished and finalised the "Development Plan of International Navigation on the Lancang-Mekong River". The four countries reached an important consensus on the second phase of improving the navigation channel in the Mekong River and stated that by 2025, 890 km of the river from the Nandeba Area of Simao Port to

Luang Prabang of Laos would be built and upgraded for vessels up to 500 DWT. Some passenger and cargo ports will also be built along the channel (Meng & Liu, 2015). The four countries also agreed on the preliminary work of the second phase of improving the navigation channel in the Mekong River, covering a 631-km channel from the China-Myanmar Boundary to Luang Prabang in Laos in September 2015. The work included channel improvement, port construction, and the building of a support and security system (Zhang et al., 2016).

8.2.2.3 Opportunities and Challenges for the Development of International Navigation

China has proposed cooperation initiatives such as the Belt and Road Initiative and the construction of the China-Indochina Peninsula Economic Corridor, which safeguards the development of Lancang-Mekong international navigation. Moreover, a series of international cooperation funds, such as the Silk Road Fund, China-ASEAN Maritime Cooperation Fund, Asia Regional Cooperation Special Fund, and Lancang-Mekong Special Cooperation Fund, also provide favorable financial options for its development. China and ASEAN have formed a new cooperation pattern in 9 areas, including bilateral, sub-regional, and "10 + 1" relationships. China has already developed comprehensive strategic partnerships with Indonesia, Vietnam, Laos, Cambodia, Myanmar, Thailand, and Malaysia, and has continued to promote political mutual trust, economic cooperation, and people-to-people exchanges, which has laid a solid foundation for the development of Lancang-Mekong international navigation.

With the signing of the Treaty of Amity and Cooperation (TAC) in Southeast Asia, Thailand has established strategic partnerships with other ASEAN countries. Open economies in the Mekong basin have formulated a ten-year development strategy and a sub-regional action plan for tourism. Thailand has seized the historical opportunity, and actively opened up a new phase in the development of Lancang-Mekong navigation by cooperating with other countries. The Golden Triangle Tourism Cooperation Plan has been passed, which combines the development of navigation with tourism and other related industries, and boosts the international tourism industry. In addition, Vietnam has also established many tourism programmes through navigation, such as the development of tourism in the triangle area of Cambodia-Laos-Vietnam and the Red River Delta.

The cooperation on cross-border shipping has been set up. The North–South Economic Corridor, the East–West Economic Corridor and the Southern Coastal Economic Corridor have helped Vietnam maximise its economic benefits from transportation hubs and promoted trade and investment among different regions in the area. On the East–West Economic Corridor, Vietnam, Thailand and Laos have signed an agreement to open a route connecting three capital cities and two large ports: Laem Chabang Port and Hai Phong Port.

The "navigable section of the Mekong River runs from Gongguo Bridge in Yunnan Province to the estuary of the river, with a total distance of 3646 km, passing through more than 100 towns and 20 cities including Vientiane and Phnom Penh." The Lancang-Mekong international navigation enables the transport of large amounts of copper, gold, silver mines, abundant oil and natural gas in Myanmar, as well as 10 billion tons of potash and forest resources in Laos. The international navigation will boost the economic development of Mekong countries, which have all set the development of the Lancang-Mekong navigation as a priority for regional economic cooperation.

In addition, based on some analysis reports on the economic impact of ports, it can be found that every 10,000 tons of throughput contributes 1.1 million yuan to a country's GDP and creates 20 jobs. The development provides more employment opportunities for people in the basin, which does not only accelerate the development of the regional economy, but also increase the living standard of local people.

Regions around the Lancang-Mekong River Basin are relatively underdeveloped in economy and navigation. The economic development mainly relies on agriculture, which is not beneficial for the development of navigation. Besides, the upper Mekong Basin is mountainous, with turbulent water flow. There are numerous shoals and reefs in navigable channels and the hydrological conditions are complicated, which requires a large sum of money for upgrading. There is a little infrastructure of ports and wharves that are open for navigation, and most of the channels are not managed or maintained.

The governance capabilities and governance systems of some Mekong countries are relatively backward. Apart from China and Thailand, which have strict rules and complete institutional mechanisms, the public governance capabilities and the service systems of Laos and Myanmar are relatively underdeveloped. There is no independent department responsible for navigation in Laos, and so it relies on the relevant departments of the central government to manage the situation "remotely and indirectly". The laws, regulations, and rules for the management of international navigation are incomplete, and at the same time, the human and material resources are insufficient. In Myanmar, the political situation is unstable and the whole country is in the hands of three parties, including the central government, the military, and the armed ethnic minorities. The fourth special zone of Shan State in the North of Myanmar is controlled by armed ethnic minorities. The central government's inability to take over has led to severe illegal smuggling and environmental damage in the region. Although the Wan Pong Port is under the management of the central government, it does not have a sufficient supply of goods.

Based on the volume of passenger traffic provided by the four countries from 2007 to 2017, the current status of development, and the future economic trends, the freight volume and the passenger volume are expected to reach 1.0305 million tons and 3.0533 million respectively in 2025; the numbers are expected to increase to 1.8487 million tons and 4.1856 million respectively in 2035. Both can see gradual development.

The ports of the four countries are in different development stages. In Laos, the infrastructure construction of ports along the river will continue to maintain the current status, and the situation is not likely to be improved unless there is external investment. According to the Ministry of Public Works and Transportation of Laos, 10 ships will be reduced each year. Laos will try to maintain the momentum and demand for upgrading port facilities, but the situation may go south. In Myanmar, the ports directly managed by the central government will benefit from government policies and funds, and the infrastructure will be improved to build the connection between Myanmar and China. In Thailand, the government will build and develop special economic zones (SEZ) in Chiang Saen, Chiang Khong and other areas to improve port facilities and services. It will give full play to logistics and trade, increase the efficiency and convenience of delivery, and promote regional economic development. China will consolidate the construction of infrastructure along the Lancang-Mekong River, and work with neighboring countries to facilitate international navigation. It will also work with Laos, Myanmar and Thailand to build a major international transportation channel connecting upper and lower Mekong countries (Li & Xiao, 2019).

8.2.3 Fisheries Development

The Lancang-Mekong River connects China and five Southeast Asian countries. It is not only an essential link for international economic development but also provides the livelihood for people in the area. It has abundant fishery resources and has the world's third most diverse fish population, with 1,148 fish species, after the Amazon and Congo River Basins. The Mekong River provides 4 million tons of fish for the people in the basin each year, and tens of millions of people from rural areas are engaged in wild fisheries, accounting for more than two-thirds of the rural population. Residents depend on Mekong fisheries for food security and household income, and it also contributes to the social and economic development in the basin (MRC, 2010a; Sun et al., 2018).

8.2.3.1 Status Quo and Management of Fisheries in Mekong Countries

In recent years, there has been an increase in the construction of hydropower stations in major river systems in China's Yunnan Province. The new aquaculture areas in the reservoir provide favourable conditions for cage culture and fence aquaculture (Qiu & Du, 2008). Each year, the central government, the government of Yunnan Province, and the construction company of hydropower stations will invest in stock enhancement in the Lancang River Basin. Xishuangbanna Prefecture had nine fisheries enhancement in the Lancang River and its main tributaries, including the Luosuo River, the Puwen River, the Daluo River, and the Nanrun River in 2015. These practices strengthened the supervision and management of implementing the compensation of hydropower projects for aquatic organisms in China and guaranteed that the projects such as fish catch over dams, artificial spawning grounds, fish hatcheries, and large-scale stock enhancements will be implemented as required to minimise the impact of dam construction on fish. The total fishery production in the basin was 41.96×10^4 t in 2016. The fish farms covered an area of 3.66×10^4 ha, and the aquaculture output was 36.51×10^4 t, accounting for 87% of the total fishery production. The output of capture fisheries was 5.45×10^4 t, accounting for 13% of the total (Yunnan Department of Agriculture & Rural Affairs, 2016).

The Lower Mekong River Basin (LMB) has the world's largest inland captured fisheries. In 2015, Laos's total fishery production was 15.86×10^4 t, and the aquaculture output was 9.6×10^4 t, accounting for 60% of the total (Lao Statistics Bureau, 2016). The output of capture fisheries was 6.61×10^4 t, accounting for 40% of the total. Around 594,000 households in Laos were engaged in fisheries, 68,000 of which worked in aquaculture and 526,000 of which worked in capture fisheries (Lao Agricultural Census Office, 2012). Fisheries produced 50% intake of protein for local people. The aquaculture and capture fisheries in the Laos basin covered an area of 79.17×10^4 ha, 7.2×10^4 ha of which was used for aquaculture. Capture fisheries included Nam Ngum, Nam Theun No. 2 reservoirs, small wetlands, irrigation reservoirs, and weirs, taking up 17.48×10^4 ha (Phonvisay, 2013).

Cambodia has the richest fishery resources among the Mekong countries. The Tonle Sap Lake, the Mekong River, and the Tonle Sap River are the country's natural freshwater fisheries. Therefore, the development of fisheries is regarded as the priority of the Mekong River's water resources development in Cambodia. The Tonle Sap Lake has a unique flood pulse system, and it is the most productive freshwater fishery around the world. Before 2000, the fisheries management of Tonle Sap Lake had been following French colonists' management, restricting the area for commercial fisheries and stipulating commercial fishing seasons. As a result, it greatly limited the fishing area of fishermen in the community. However, the fishery policy has changed since 2000. The Cambodian government has cancelled all commercial fisheries and divided fish protection areas and community fishing areas. Under the supervision of the township government council, a fishermen management committee has been established to formulate management rules. By 2013, 516 community fisheries had been established, and many farmers in the community had actively participated in capturing fish (Lv & Wang, 2021). In 2016, the total output of freshwater fisheries in Cambodia was 68.42×10^4 t, 51.51×10^4 t of which came from the output of capture fisheries, accounting for 75% of the total, while the output of aquaculture was 16.91×10^4 t, accounting for 25% of the total. About 530,000 households in Cambodia were engaged in capture fisheries and aquaculture, 460,000 of which worked in capture fisheries, and 80,000 of which worked in aquaculture (Cambodia National Institute of Statistics, 2015).

In the Mekong River's Vietnam basin, aquaculture took up an area of 78.51×10^4 ha, most of which was in the Mekong Delta, covering an area of 77.13×10^4 ha. There was only a little aquaculture in the central highlands, which covered 1.38×10^4 ha. The fishery production totalled 304.72×10^4 t in 2016, with 84% aquaculture and 16% capture fisheries. In the same year, the total fishery production in the Vietnamese Mekong Delta region was 300.78×10^4 t, 253.66×10^4 t of which was from aquaculture, and 47.12×10^4 t was from capture fisheries. Aquaculture in the Mekong River played an essential role in Vietnam in 2016, accounting for 70% of the national aquaculture output (Vietnam General Statistics Office, 2018). By contrast, there was only 3.94×10^4 t of fishery production in the central highlands.

In Thailand, the output of capture fisheries in the Mekong River Basin was 90×10^4 t, 70×10^4 t of which was from fish, and 20×10^4 t of which was from other aquatic organisms. The output of aquaculture was 6.19×10^4 t (Mahasarakarm, 2007), and the area for aquaculture in the northeast took up 1.88×10^4 ha, 1.11×10^4 ha of which was used to produce fishery products for household consumption, and 0.77×10^4 ha of which was used to produce fishery products for sale. 88,000 families worked in freshwater aquaculture, accounting for 3.2% of the area's total agricultural population (Thailand National Statistical Office, 2014).

Comparing the differences in fishery development, Vietnam has the highest fishery production among the five Mekong countries, accounting for 58% of the total in the basin, and it mainly focuses on aquaculture and commercialised fishery products. Thailand ranks second in fishery production in the basin, accounting for 18% of the total. However, Thailand mainly relies on capture fisheries, so most of its fishery production is consumed by local people. Cambodia ranks third, accounting for 13% of the total in the basin. Since it mainly depends on capture fisheries, the production can barely meet its own needs, and sometimes it even has to import from other countries. China's fishery output ranks fourth, accounting for 8% of the total in the basin. Aquaculture accounts for most of the output, and most fishery production is commercialised. Laos has the lowest fishery output, accounting for only 3% of the total in the basin. The proportion of aquaculture and capture fisheries output is similar to Cambodia. The production can barely meet its own needs, and sometimes it has to import from other countries. In general, Vietnam has taken full advantage of fishery resources in the basin, followed by Thailand, Cambodia, China, and Laos (Wang, 2019).

The LMB cooperation of sustainable development is based on the Mekong River Basin Sustainable Development Agreement signed by Laos, Thailand, Cambodia, and Vietnam. The unified management agency is MRC, which was established in 1995. The MRC abides by the agreement of sustainable development and formulates plans and management of the Mekong fisheries. Although fishery products are the primary source of protein for people in the basin, the industry has not received much attention due to its considerable input and low output. Mekong countries have different needs for the development of fishery resources due to their different geographical locations and economic development, and thus very little cooperation in fisheries has been carried out among Mekong countries. Moreover, the adverse impact of hydropower development on fisheries is a concern for lower Mekong countries, so most cooperation was seen in 2015 between China and Laos. The two countries signed an agreement on protecting fishery resources and worked together on stock enhancement and ecological conservation. As two major hydropower developers, China and Laos's cooperation shows respect for other countries in the basin (Yu, 2017). In addition, the technical advisory agency of the Lower Mekong fisheries management, which was established in 2000, formulated the 2018–2022 Mekong fisheries management system, including “the Mekong Basin-wide Fisheries Management and Development Strategy (BFMS) 2018–2022”. This regional strategy focuses on inland capture fisheries and prioritises the sustainable use and protection of fish resources.

8.2.3.2 Challenges and Countermeasures of Fishery Development in the Mekong River

At present, the Mekong River’s freshwater ecosystems (lakes and rivers) are being severely impacted. The aquatic organisms, especially fish resources, face severe challenges, including overfishing, large-scale hydropower development, invasion of alien species, and water pollution. The entire basin has shown a trend of a significant decline in fish species and population. Some species are endangered, and some have even become extinct (Liu et al., 2008).

The most negative impact is the construction of hydropower dams, which results in the block of the upstream channel of spawning, the death of downstream broodstock after breeding, and the deaths of juvenile fish when they go down through the dam, or when they are in the downstream of the dam and in the hydropower system. During the slow migration and periodic entry into the estuary, the continuous fatal impact on the juveniles when they pass through dams will change the original growth pattern of juveniles in the reservoir. The Mekong hydropower dams have become an insurmountable obstacle for the species that need to migrate to complete their life cycle, thus seriously changing and destroying the habitat of fish, along with their migration and reproduction cycle. The populations of short-distance and long-distance migratory fishes have declined, leading to destroyed biodiversity. In addition, the impoundment of the dam has also increased the nutrients in the submerged zone, which would affect water productivity. The construction of water conservancy and hydropower projects has changed the river’s hydrological conditions to a certain extent, affecting and destroying the conditions for migration, habitat, feeding, and reproduction of some species (Ferguson & Xu, 2012). The development of hydropower will not only adversely affect the integrity of the Mekong ecosystem but also threaten the economic income, sources of nutrition, and social benefits brought by it. The LMB has the world’s largest inland fisheries, with the total fish catch estimated at 3 million tons, 80% of which comes from capture fisheries, and the annual wholesale transaction volume is about US$20–30 billion. According to a report by the International Center for Environmental Management (ICEM) in 2010, the construction of dams on the mainstream of the Mekong River led directly to US$4.76 billion economic losses for fisheries. Moreover, the hindrance of fish migration led to a decline in fish production, which was undoubtedly a heavy blow to the residents of the Mekong River who relied on traditional fishing for their livelihoods and the fragile inland fishery economies, such as Laos, Cambodia, and Vietnam, pushing local low-income families further to extreme poverty (Wei & Zhang, 2015).

In addition, due to the unique geographic location and characteristics of the Lancang-Mekong River Basin, there are incredibly diverse species of fish. Therefore, it is a great challenge to fully understand the diversity and distribution of fish in the basin and explore the variation of diversity and its attribution on the basin scale (Li et al., 2019). Apart from the difficulties in obtaining information, the existing cooperation mechanisms lack sufficient political mutual trust. Several mechanisms are overlapping, and the laws are incomplete. Moreover, the intervention of countries outside the basin has made the initially complex cooperation in the basin more complicated and increased the uncertainty of cooperation (Yang, 2017a, 2017b). The fishery group under the MRC is mainly responsible for organising scientific investigations, information sharing of fishery resources, improving fisheries management skills and capacity in communities, and coordinating and managing fisheries among countries. However, the people in the group have not done their best in their work, and many scientific management methods and close joint-management mechanisms have not yet been established.

To address the current and emerging fisheries management issues, riparian governments have focused their policy priorities on improving productive capacities, protection and conservation of critical habitats and resource enhancement, modernisation of the traditional systems of extensive resource use and their equipment and techniques, fostering of community-based approaches, and promotion of the shift from subsistence to commercial production by professional fishers and fish farmers producing for the market. To complement the national measures, the MRC strives to foster regional efforts towards sustainable management and development of the Mekong fisheries, including through the sharing of technical know-how on fisheries management, raising awareness on the sector's significance for the Mekong's environment and its people, and promoting an integrated approach with other sectors. The MRC has also developed monitoring programmes and technical guidelines to track fisheries' status and trends and promote participatory fisheries management or co-management by members of fisheries agencies and user communities, leading to better management results and sustainable use of fisheries resources. Under the MRC SP 2021–2025, through which the Basin Development Strategy (BDS) 2021–2030 will be implemented, the MRC utilises its fisheries expertise to support the member countries via its regional Expert Group on Environmental Management in managing risks to food security from excessive pressure on fish stocks and in improving understanding of the gender and vulnerability aspects of basin-wide fisheries management (MRC, 2017).

8.3 Lancang-Mekong River Basin Ecohydrological Management

8.3.1 Main Ecohydrological Problems

8.3.1.1 Environmental Flow

Environmental flow describes the quantity, time, and quality of water flows required to sustain freshwater and estuarine ecosystems and the livelihoods and well-being of the people who rely on them, which is also known as ecological water demand, environmental water demand or ecological water demand in watercourse (Dong et al., 2020; Pastor et al., 2014). It is the core problem of sustainable water resources management in the river basin to scientifically estimate and sustain the environmental flow.

Significantly affected by tropical monsoon climate, the precipitation distribution through a year in the basin is quite uneven. About 80% of the precipitation and 75% of the annual runoff occur during the rainy season (Liu et al., 2020a, 2020b). Influenced by distinct wet and dry climate, climate change and El Nino, floods or droughts of varying degrees frequently happened in LMRB (Chen et al., 2020). Since the 1980s, the drought and flood disasters have occurred frequently in the LMRB due to the interaction of multiple monsoon systems (Hundertmark, 2010). In this context, the security of environmental flow has become the major ecohydrological problem confronted by LMRB.

Over the past 30 years, LMRB basin has had 4 severe droughts, one of which was in 1991–1994, it was a period longer than 38 months. The driest one was in 2015–2016 with a drought area of up to 75.6% (Guo et al., 2017). From the end of 2014 to 2016, countries around the basin suffered drought of varying degrees affected by the El Nino phenomenon. Back then, the water level of the Mekong River dropped to the lowest in nearly 90 years and a large amount of salt water invaded the Mekong Delta (Larson, 2016). It is generally of long duration and high intensity the droughts appeared in the Delta area (Guo et al., 2017). The droughts can result in unprotected environmental flows, impairing the irrigated agriculture, destructing the river ecological balance, and polluting the (drinking) water.

A special flood adaptive ecosystem has been created by the frequent floods. For the past few years, a great number of dams have been constructed along the basin, effectively decreasing the flood risk. However, the yearly flood pulse of the Mekong River has been altered, compromising the ecological system that is sensitive to the flood pulse. The drop of flood pulse amplitude is estimated to reduce the transportation of silt and nutrient substances and exert negative influence on aquatic habitats that depend on large seasonal water level fluctuations (Matti & Juha, 2008). Furthermore, the yearly pulse change of flood and short-term water level change also affect the agricultural activities on flood plains and riverbanks, for instance, the Tonle Sap River, Tonle Sap Lake and its floodplains, Mekong Delta and so on (Arias et al., 2012; Binh et al., 2020; Matti & Juha, 2008). Studies show that the flood peak will be delayed by one month if the flood pulse reduces 50%, which would prevent the Mekong River from flowing into Tonle Sap Lake (Pokhrel et al., 2018).

8.3.1.2 Water Quality

In general, the water quality in the basin is good. From the perspective of space, in the upstream is better than in the downstream and the in main stream is better than in the tributary.

The basin is naturally advantageous in geographical location with abundant mineral resources. With the exploitation of nonferrous metal ore, the surface heavy metal elements after exploitation, were washed into the river by precipitation, leading to the increase of heavy metal concentration in the river sediment. The majority of the middle and lower reaches of the Lancang River have good water quality, but some reaches (near Gongguoqiao) have enrichment coefficient of heavy metal elements such as Cu, Pb and Zn more than 2, representing mild or moderate pollution (Zhang et al., 2014).

Domestic sewage, industrial waste water and residual nitrogen and phosphorus from farmland drainage are the key factors of the basin chemical pollution. The average annual total phosphorus content in the Langcang River Basin is 1.6×10^4 to 3.9×10^4 tons, among them, soil erosion accounts for 60%. Influenced by agricultural production and other human activities, the spatial distribution of phosphorus content shows an increase trend from the upstream to the downstream (Zhang et al., 2020). In three sub-basins of the Mun River, the tributary of the Mekong, the maximum parameter concentration of NH3-N, fecal coliform bacteria (FCB) and colibacillus have exceeded the surface water quality standards permitted by the Pollution Control Department (PCD) of Thailand (Yadav et al., 2019). Furthermore, the invasion of large amounts of suspended solids and silt has further made the increase of the total phosphorus content in water (MRC, 2018).

With economic and demographical development, infrastructure construction and sustainable increasing of mining and energy demands, large quantities of factory sewage and domestic waste water are discharged in to the rivers in the basin, which make the water pollution more severe and, as a result, the water quality shows a deteriorating trend (Chea et al., 2016; Su et al., 2011).

8.3.1.3 Soil Erosion and Sedimentation

While the erosion is strengthening in the basin, the sediment transportation to the delta is decreasing because of land use and coverage change, dam construction and flow regime change.

Over the past 50 years, with the rapid development of social economy, demographic growth and land use change, the average erosion ration in the basin has reached 5000 t/km^2/year (Anthony et al., 2015), which is the medium erosion level. In addition, the erosion intensity is now increasing due to the change of climate and land use (Chuenchum et al., 2020). The sediments generated during the erosion process make the river turbidity of the Lancang-Mekong River higher. On the other hand, in the Mekong Delta, the amount of sediment inflow is decreasing and some shorelines are eroding at a rate of 50 m per year (Marchesiello et al., 2019). Since 2015, the sandbanks downstream has obviously shrunk. The direct factor for such a phenomenon is the increased erosion force and decrease of sediment inflow, which is mainly because of flow velocity increasing and shear runoff stress, as well as human activities such as dam building, sand mining and urbanisation (Guo et al., 2020).

As the increase of sand demands in foreign market, a large gravel export business has begun to exploit the sediment in the Mekong basin. In 2011, Lao People's Democratic Republic, Thailand, Cambodia and Vietnam exploited 34.48–55.20 million tons (density is dry 1.6 tons per cubic meter) of sediment in the Mekong mainstream, among which, Cambodia was the largest one for such extraction in 2011–2012 (60%), followed by Vietnam (22%) and Thailand (13%) (Bravard et al., 2013). As the sand mining amount is greater than the sediment flux of the river channel, the elevation of the riverbed will decrease, making the riverbank less stable (Hackney et al., 2020; Jordan et al., 2019). According to the Mekong River Commission Report 2018, the sediment load flowing into the Mekong Delta was 143 million tons in 2007, however, it is predicted to be less than 500 million by 2040 due to the influence of the main stem and tributary water conservancy projects (MRC, 2018). The Mekong Delta is the third largest delta plain in the world and sediment has brought in abundant nutrients and huge economic benefits. This development will certainly compromise the production of fishery and planting industries in the delta, as well as the navigation, hydroelectric power generation and ecological security in the basin (Hou et al., 2020).

8.3.1.4 Aquatic Organism

The Lancang-Mekong River is one of three rivers with the highest freshwater biodiversity in the world. According to the estimation, there are at least 890 freshwater fish (Rainboth et al., 2012), which is only second to the Amazon. Dams that have been built and are being planned in the river basin have changed the eco-hydrological conditions by regulating the natural flow of the river, which may significantly affect the fisheries development, wildlife habitat and biodiversity. These dams will affect more than 50 species of fish and dozens of millions of individuals which spawn and migrate in the basin. Fish migration may be disrupted and they may be trapped in the dams at larval stage, making impact on eggs and larvae, which flow downstream to sustain fisheries replenishment. The mitigation technologies, such as existing fishway, fish lock and fish hoist are incapable of coping with the large biomass of fish migratory scale (Dugan et al., 2010). A total of 78 dams that have been built in the tributary which will immensely reduce fish reproduction and biodiversity. Among these, Lower Se San 2 has had the greatest impact on fish biomass (LSS2, the fish biomass declined 9.3% in the river basin), followed by Se Kong 3d (2.3%), Se Kong 3u (0.9%) and Se Kong 4 (0.75%). By 2030, the additional biomass loss caused by a further 27 dams planned on the tributary will be about 39% (Ziv et al., 2012). A total of 13 species of fish in the Lancang River system are listed in the China Red Book of Endangered Animals (Fish), accounting for 14.13% of the total number of endangered fish (Kang & He, 2007). In the reservoir area above the dam, exotic fish, such as cyprinidae, Taihu new whitebait fish, etc. have been imported and the changes of water environment are more suitable to the dispersal and reproduction there (Havel et al., 2005), in this way, they can be propagated rapidly. In the 1960s, the production of fishing (indigenous) fish was 7 times that of farmed (exotic) fish. In the 1980s and 1990s, it was quite the opposite, the natural fish production was only one-seventh that of farmed fish, and the indigenous fish were under severe threat (He et al., 2007). During the process of dam impoundment and operation, the elimination of native fish and introduction of exotic fish will make the fish trophic population change.

The natural longitudinal connectivity of a river is a corridor for the flow of energy, material, and fish from upstream and downstream (Santos et al., 2006). Fish population structure along these longitudinal gradients is a good indicator of overall river ecosystem health. The dams, as the obstacles, destroy the longitudinal connectivity of fish assemblages and affect free migration of fish along the rivers (Schiemer, 2000). Studies revealed that the biological integrity index F-IBI of fish in the main stream was 0.41 $km^{-1}$and that in the tributaries was 0.17 km^{-1} before the operation of Xiaowan Dam, reflecting the diversity of habitats and fish fauna. However, the values have respectively dropped to 0.01 and 0.09 km^{-1} afterwards, indicating the habitat and fish fauna homogenisation (Li et al., 2013). After the completion of Manwan dam, the diatom in phytoplankton dominated but the total number of species significantly decreased. The phytoplankton species decreased from 41 to 35, in particular, in the alluvial zone under the dam. With the construction and operation of Xiaowan dam upstream, phytoplankton communities in Manwan Reservoir and downstream areas quickly responded to further changes in the environment. During the construction of Xiaowan dam, in the alluvial zone of Manwan Reservoir, the abundance of phytoplankton decreased from 1.54 × 105 ind./L to 0.05 × 105 ind./L, and in the static water zone, it decreased from 9.34 × 105 ind./L to 0.10 × 105 ind./L (Fan et al., 2015).

8.3.1.5 Underground Water

Underground water is a crucial resource of the Mekong river. According to estimates, at the time of writing, there are over 1 million wells in the Mekong River Delta region shared by Cambodia and Vietnam for the exploitation of groundwater resources so as to meet local production and living needs (Erban et al., 2013). The global groundwater data from the International Groundwater Resources Assessment Centre (IGRAC) directory indicate that basin groundwater withdrawals are about 550 million m^3/year (Ho et al., 2019), which is distinctly higher than that in the1960s. Currently, the dependence on underground water is increasing, especially in Cambodia and Thailand, and this water has become the major source of drinking water supply (Ho et al., 2019). Studies indicate that the excessive exploitation of underground water has made a large part of the Vietnamese side of the Mekong River Delta subside (Erban et al., 2014). The average descending range during 2002–2017 was up to 18 cm (Minderhoud et al., 2017). In some of the delta areas, there are problems, such as the combined effects of rising sea levels due to climate change, depletion of aquifers, deterioration of water quality and intrusion of salt water (Erban et al., 2014; Hamer et al., 2020; Smajgl et al., 2015). Furthermore, the climate change has altered the precipitation and temperature across the basin, the resultant change of underground water supply mode and the downstream flood pulse will affect the underground water system in delta region (Smajgl et al., 2015).

8.3.2 Current Treatment Measures

8.3.2.1 Scientific Evaluation and Regulation the Environmental Flow

From the perspective of water ecological protection and management in the basin, it is vital to scientifically estimate, safeguard and regulate the ecological environmental water demand. According to the classification coefficient of ecological environmental water demand (GCEWR) and ecological runoff (ER), the minimum, the suitable and optimal environmental flows of the Lancang river channel are respectively 142.53×10^8 m^3, 286.46×10^8 m^3 and 385.96×10^8 m^3, separately accounting for 18.63%, 37.45% and 50.45% of the natural runoff (765×10^8 m^3) (Hu et al., 2009). The ecological flow management should also sustain the aquatic habitat. A case study of Chinese knotting fish, the highest priority fish in the middle and lower reaches of the Lancang River, the optimal ecological flow during spawning period and adult period is 2100 m^3/s and 1200 m^3/s, respectively (Peng et al., 2020).

The building of reservoirs can substantially regulate the environmental flow of the downstream in the basin and effectively improve the guarantee rate of environmental flow during the dry season. There are six dams in the upstream of the main stem of the Lancang River. They can reduce flood peak discharge and reduce sediment flux in China (Fan et al., 2015). Meanwhile, they can effectively regulate the volume of runoff in the basin (Rasanen et al., 2012; Tang et al., 2014a, 2014b; Yun et al., 2020a, 2020b). The construction of these dams has positive impact for the ecohydrological processes in the basin. The operation of upstream reservoirs can release the water stored in the rainy season to mitigate the shortage of water in the dry season, ensuring its environmental flow and promoting the stable development of agricultural and ecological system downstream in the Mekong delta (Kondolf et al., 2018). In face of the severe drought in Southeast Asia at the end of 2015, water was continuously released through the joint operation of reservoirs, which greatly mitigated the drought in the downstream countries (Zeng, 2017). Compared with the long-term average level, the drought had reduced the flow by 16%. Nevertheless, due to the urgent discharge of Chinese dams, the flow in the dry season has increased, Ultimately, it was conducive to alleviating the potential effects of the drought. During the period from March to May, 2016, Jinghong reservoir discharged 12.65 billion cubic meters in total, which was equivalent to 40–89% of the flow in the Mekong River's various reaches. Emergency water replenishment increased the water level or flow along the mainstream of the Mekong River by 0.18 –1.53 m, which was 602–1010 m^3/s. Without these emergency discharges, the flow of Jinghong would have been reduced by 47%, Qingsheng by 44%, Langkai by 38% and Shangding by 22%. In addition, the emergency discharge eased the salt water intrusion to the Mekong Delta.

8.3.2.2 Improvement of Regional Water Quality Monitoring Capacity

In terms of the hydrological and ecological issues in the basin, the countries and organisations along the basin strengthen the monitoring to deal with problems of water quality and underground water. In 1985, in an effort to maintain the proper level of water quality in the entire Mekong River Basin, the Mekong River Commission established water quality monitoring networks in the Lao People's Democratic Republic, Thailand and Vietnam (Cambodia joined in 1993) to detect the water quality change for necessary measures. So far, there have been 132 monitoring points in total, 33 of which are monitoring sites established in the 2000s and 99 old points established before 1995 (Chea et al., 2016). Since 2010, MRC and its member countries have routinely monitored the water quality of the Mekong River and its major tributaries on a monthly basis by measuring 19 water quality parameters at 48 stations, 17 of which are in the Mekong River, 5 stations in the Bassac River, and 26 stations on tributaries of the Mekong River (https://www.mrcmekong.org/our-work/functions/basin-monitoring/water-quality-monitoring/). The monitoring has effectively supported water quality management and early warning in the basin.

8.3.2.3 Aquatic Conservation

A series of measures have been taken to mitigate the impact of human activities and climate change on aquatic life in the basin. The critical tributaries have been identified and natural reserves have been established along the river so as to protect the habitat and native fish populations. Ecological reservoirs have been rebuilt and the ecological environment monitoring and evaluation system together with the fishery administration have been improved (Huang, 2013; Yuan, 2012), when planning the number and location of hydroelectric dams, appropriate removal of dams on major tributaries and enhancement of indigenous fish stocks. Furthermore, fish passage facilities have been established in dams along the main stream of the Lancang River, including fish hoist, fish lock and fish ladder (Huang, 2013). Germplasm conservation areas have been established in the main growth and breeding areas of cross-border fish germplasm resources with high economic value and genetic and breeding value, and corresponding management methods have been formulated to strengthen and standardise the management of the conservation areas. Secondly, a regional gene bank centre for the germplasm resources of cross-border migratory fish has been established to strengthen the protection of the genetic germplasm resources of migratory fish, in particular, the rare genetic germplasm resources of migratory fish, strengthening the relevant technical research and advancing the sustainable utilisation of resources (Liu et al., 2008). The ecology scheduling has been implemented in the dams and reservoirs operation management in order to ensure that the discharge of water can sustain the ecological function of the river and protect it from being damaged. Furthermore, the flood peak of artificial flood discharge in the flood season has been adopted based on the time of year when most fish in the basin migrate. Meanwhile, special attention has been paid to the flood process that is basically consistent with the natural conditions to meet the migratory fish demands. When conditions allow, layered discharge can be adopted to increase the drain of surface water, raise the temperature of drainage water, prolong the discharge time, reduce the discharge intensity and reduce the impact downstream (Chen et al., 2007). In a word, the ecology scheduling has been adopted to compensate the environmental demands of river ecosystems on the quantity, quality and temperature of water and keep the flood discharge similar to the natural flow state of rivers, minimising the stress on aquatic organisms caused by adverse environmental effects including low-temperature water and supersaturated gas. At last, fish hatcheries can be built to propagate and set free the native fish (Li et al., 2013). The international aid funds and talents can be utilised to build the endangered fish domestication and breeding base. Key technologies for the domestication and breeding of rare and endangered species can be explored and establish a system for artificial release of endangered fish (Liu et al., 2008).

8.3.2.4 Cooperation of Hydrology and Ecology in River Basin

The flow of water resources in the basin is transboundary. Thus cooperation of water resources management is a necessity to improve and solve the ecohydrological problems in the river basin (Liu et al., 2020a, 2020b). The Lancang-Mekong Cooperation (LM cooperation for short) mechanism established at the end of 2015 is the first regional cooperation initiated by the countries in the basin. Almost all aspects of basin management are included within the Lancang-Mekong cooperation mechanism, but there have been five priority directions: connectivity, capacity of production cooperation, cross-border economic cooperation, water resources cooperation, agriculture and poverty reduction cooperation.

Water resource cooperation, as one of the five priority development directions (connectivity, productive capacity, cross-border economic cooperation, water resources, agriculture and poverty alleviation), dedicates to realising the reasonable distribution, fair utilisation of water resources and sustainable economic development of countries in the basin (Feng et al., 2019). In August, 2020, the third leaders' meeting of Lancang-Mekong cooperation was successfully held, promoting cooperation in the comprehensive development stage and sending a positive signal of solidarity, cooperation and common development among the six Lancang-Mekong countries. China will start to share annual hydrological information of the Lancang River with Mekong countries from the same year.

At the present stage, over 10 multilateral documents on cooperative river basin flood management have been signed in terms of flood disaster control for countries in the basin, involving identification and responsibility of flood disaster prevention and control, flood monitoring and early warning, and emergency response of flood control. The flood prevention and control work will be promoted comprehensively through multiple methods, such as, high-level government visits, expert exchanges and data and information sharing (Wu et al., 2020). The item 6 of The Five-Year Plan of Action for LM Cooperation (2018–2022) emphasised that the emergency management of flood and drought disasters in the Lancang-Mekong region should be strengthened, and a joint assessment of flood control and drought alleviation in the Mekong river basin should be implemented. China proactively deepened the cooperation on data sharing with MRC member countries, and signed the Steps on Data and Information Exchange and Sharing and the Memorandum of Understanding on the Provision of Daily River Flow and Rainfall Data at Two Monitoring Stations in Yunnan Province during the Rainy Season. In this way, water conservancy construction, flood control, drought relief in basin countries have been significantly advanced. In terms of irrigation, China responds to demands of downstream countries in real time and increases the discharge of the upstream reservoirs to satisfy the irrigation and ecological conservation needs of downstream countries.

8.3.3 Future Challenges and Countermeasures

In future, the flood intensity and frequency in the Mekong River Basin will increase and the extreme weather phenomena will be exacerbated (Ding et al., 2020; Wang et al., 2017). In the context of multiple climates and land use in the future, the soil erosion ratio and sediment yield in the river basin will change rapidly (Chuenchum et al., 2020). The probability for the upper and lower reaches of the Lancang-Mekong River to be moist in the same period will increase greatly, meanwhile, the probability of the drought in the same period and the difference between the upper and lower reaches of the river will decrease (Yun et al., 2020a, 2020b). It is also worth noting that the variability of temperature and precipitation will not only affect the hydrological regime of the basin, but also the dam operation modes (Zhao et al., 2012). The water power resources in the basin are abundant and the potential of hydropower is still tremendous (Liu et al., 2020a, 2020b). It is the future focus to comprehensively and rationally use the ample water power resources. At present, there are 452 reservoirs that have been built, under construction or planned along the basin, with a total storage capacity of 133.95 billion m^3 (Hou et al., 2020). As of 2016, there were 136 dams in the Mekong river basin, 26 of which have been built, 16 were under construction and 94 were under planning (Liu et al., 2020a, 2020b). How to coordinate hydropower development with hydrological and ecological protection and how to study the positive role these reservoirs and dams may play in the regulation of environmental flow are the problems that need to be addressed urgently. In addition, it requires the focus of countries along the river basin about the scientific planning of the proposed reservoirs and the joint operation and management of the existing reservoirs. As a result, in future, the focus will not only be on reducing the risks of drought and flood caused by climate change, but also on exploring the operational rules for dams (Ding et al., 2020). The number and positions of hydropower stations to be planned shall be taken into consideration to deal with the uncertainty in the flood control process of damming and adapt to the regional water resource management. Countries should tap their potentials, improve the level of infrastructure, strengthen the joint operation of water conservancy projects (Fan et al., 2015). At the same time, as new dams are brought into operation, they should also protect the growth and reproduction of life in the river basin through the way they operate so as to make the water release process closer to the natural state of the river (Li et al., 2013).

Water quality management will also be the crucial challenge confronted by the basin. The future of the basin is closely linked to the livelihood of population in riparian countries, which means that a unified and coordinated management is required (Dugan et al., 2010). Dominated by developing countries, the basin is susceptible to the deviation in terms of the economic development and the resulting water pollution problems. That is to say, the short-term economic boom is at the cost of the ecological environment. Due to the integrity and interconnection of the water area, the neglect of environmental protection by any country will easily result in the destruction of the entire ecosystem of the river basin and make other countries suffer (Rosegrant et al., 1994). The basin covers six riparian countries with different, incomplete and improper water legislation and policies. According to their separate development requirements, they have respectively released the Joint Declaration of the Water Resources Utilisation Principles in the Mekong River Basin, The Cooperation Agreement for the Sustainable Development of the Mekong River Basin, the Strategic Framework of the Greater Mekong Sub-regional Economic Cooperation Plan and the Kunming Declaration. These conventions and agreements are formulated for the management of the river basin and international cooperation. As a matter of fact, they are of virtually no legal status, and they have not come into an agreement among the six riparian states, as a result, the comprehensive water pollution management cannot be implemented at present (Dugan et al., 2010).

Data sharing and information connectivity are also the pressing challenges to be solved. Recently, the MRC set up the Mekong River Basin Tool Database. However, the information about the water regime of the basin is obsolete and the contents are incomplete, in particular, in terms of deforestation, soil erosion and sediment deposition. Meanwhile, some NGOs are dedicated to participating in the management and protection of this basin. The current cooperation mechanism fails to provide effective paths and restricst the channels for obtaining the scientific data or true information for understanding the current situation of the river basin. Consequently, some of the NGOs are susceptible to doubt the development behavior or construction projects of countries in the river basin so that they protest for the implementation in the name of environmental protection. Furthermore, one-sided information will also rouse the opposition of people in these countries, intensifying the international relationship, which is not conducive to creating a cooperative atmosphere of mutual trust and interoperability for the river basin.

The following measures shall be taken to cope with the challenges described above:

1. Actively cope with the impact of climate change. With the rise of global temperatures, extreme climate events in the basin have increased significantly. Therefore, the quantitative assessment of the impact of climate change on the basin is vital (Bi et al., 2015). Despite the decisive effect of precipitation on water resources in the river basin, the impact of other climatic elements is non-negligible. Consequently, the climatic elements shall be taken into consideration in future so as to comprehensively evaluate the impact of climate change on the basin (Yun et al., 2020a, 2020b). In addition, the focus shall also be on the accurate prediction and early warning of droughts and floods (Ding et al., 2020). Restricted by the great uncertainty in the study of water resources management under climate change (Wu et al., 2013), the flood control institutes of river basins should also update flood control standards in a timely manner in the future and strengthen the flood forecast and early warning in the flood season. In this way, the decision-makers can formulate the effective mitigation strategies and minimise the impact of droughts and flood disasters (Huang et al., 2018; Tang & Cao, 2019).
2. Coordinate the relationship between the dam construction and water ecological protection. The potential environmental and geopolitical risks associated with Lancang-Mekong cascade dams make it a necessity for a long-term basin-wide monitoring of land and aquatic organisms so as to ensure the sustainable development of the basin (Fan et al., 2015). The operation rules of dams should be explored continuously and the number and locations of hydropower stations under planning should be taken into consideration in order to deal with the uncertainty of the flood control process of damming and adapt to the regional water resource management (Ding et al., 2020). Countries should tap their potentials, improve the level of infrastructure and strengthen the joint operation of water conservancy projects (Feng et al., 2019). Scientific dam location selection can improve the quality of the water conservancy project, which is the premise of rational utilisation and regulation of river basin water resources (Deligiorgis et al., 2015). The long-term water resources, population, farmland, annual rainfall and channel width should be fully considered (Yang, 2017a, 2017b) and the digital elevation model shall be utilised for the auxiliary judgment (Michael et al., 2019). Furthermore, the impact for the built dams on the ecological environment of upstream and downstream shall be factored in. Systematic and scientific simulation of dam site selection and construction process is the route one must take for intelligent dam construction in future (Liu et al., 2021).
3. Strengthen the study on the law of water and sediment. In terms of ecological environment in the basin, the priority of the future study should be the average annual sediment yield and sediment transport and its interannual variation. The sediment yield and transport can be calculated from top to bottom by simulating the sediment process of the entire basin, or estimating the sediment inflow in the

Mekong River Delta from bottom to top by taking the formation process of the delta as the entry point. With the scarcity of observation stations and poor data quality, a distributed physical hydrological model with high spatial–temporal resolution should be established, so the ground observation data and the rapidly developing satellite remote sensing product can be effectively used. The model can be used to analyse the sediment yield and transport problems in the entire basin based on the general soil erosion equation in a detailed manner (Chuenchum et al., 2020).

4. Enhance the awareness and understanding of the basic situation of water resources and ecological environment in the region and advance the authority release of geographic information. Based on the improvement of the monitoring mechanism of ecological environment, the soil and water conservation shall be further intensified. Meanwhile, the regional vegetation survey and research should be vigorously conducted and the franchising work should be actively promoted so as to integrate it into the Lancang-Mekong Cooperation strategy. In addition, formulating a scientific conservation plan is also one of the effective measures at the watershed scale (Li et al., 2019). For instance, proactively advance the thematic design research on fish hoist and fish collection and transportation system and refine the conservation plan to protect the aquatic biodiversity in the basin from being further destructed. In the future, it is pressing to develop long-term basin-wide land and aquatic monitoring programmes so as to ensure the sustainable eco-hydrology in the basin (Fan et al., 2015).
5. Continue to deepen regional cooperation. In 2014, the establishment of Langcang-Mekong Cooperation Mechanism has provided a new platform for the six countries in the river basin to have in-depth exchanges, share experience in water resources management and jointly tackle the challenge of climate change. In the future management of river basin, countries should strengthen cooperation in addressing climate change, disaster prevention and mitigation, flood and drought, landslides and other issues regarding hydrological and ecological security. In this way, the Lancang-Mekong Water Resources Cooperation Center can act as the supportive platform. The Five-Year Action Plan on Lancang-Mekong Water Resources Cooperation (2018–2022) should be implemented so as to establish the information sharing platform for Lancang-Mekong water resources cooperation. The technical cooperation and exchange should be strengthened through policy dialogue, data and information sharing and cross-border water resources management. The joint research and analysis on Lancang-Mekong water resources should be carried out and the public should be encouraged to participate and exchange their opinions, in this way, the capacity of building on water resources management can be strengthened and the practical cooperation on climate change adaptation, dam security, drinking water security and flood and drought disaster management can be advanced (Liu et al., 2020a, 2020b; MRC, 2020). In addition, based on the environmental protection development plan of the six countries in basin, the "Green Lancang-Mekong Program" should be proactively implemented. The focus shall be the advancement of air and water pollution prevention and control and ecosystem management cooperation

and the enhancement of the communication with relevant sub-regional mechanisms. Meanwhile, the public awareness of environmental protection should be raised through strengthening environmental capacity building and cooperation in publicity and education (MRC, 2018). To summarise, there is no other way to make the water resources cooperation feasible in the LMRB except for proactively responding to the challenges of environmental change on eco-hydrological safety, developing and refining the dialogue and cooperation mechanisms, and realising the unified development and benefit sharing in the river basin (Sun et al., 2018).

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Chapter 9
Basin Governance and International Cooperation

Shaofeng Jia, Yu Wang, Hoaithuong Do, Boris Gojenko, and Caixia Man

Abstract Integrated basin governance means integrated water governance taking basin as the spatial unit. It deals with rules of integrated water resources management, including the establishment of governance bodies, the definition of interests and roles of stakeholders, the principles and regulations of decision-making, and the arrangement of decision-making procedures. For trans-national basins, international cooperation for integrated basin governance is necessary that is mainly embodied by basin cooperation mechanisms. The implementation of international basin cooperation depends on a number of mechanisms. There are about fifteen cooperative mechanisms in the Mekong Region divided into two groups: intra-regional mechanisms (cooperation among Mekong countries) and mechanisms between Mekong countries and non-basin partners. MRC, GMS and LMC are the three most active mechanism. Within the Lancang-Mekong River Basin, each country has particular perspectives about international basin cooperation. China is very active in Basin cooperation and has invested a lot of resource in this regard, but is sensitive to the intervention from

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countries outside the region. Cambodia and Laos, with most territory located within the Basin and essential or even majority of foreign investment from China, are active to diversify their international cooperation while maintaining close cooperation with China. Most of the inflow of foreign investments into Myanmar comes from Asian countries, followed by European countries and the United States, and is influenced by its domestic political situation. Thailand has been a relatively stable recipient country of foreign investment for a long time and has benefited significantly, it has now become a donor country, playing an important leading role in basin cooperation. Vietnam's foreign investment mainly comes from Japan, Korea, and ASEAN. Vietnam plays the leading role in environmental cooperation in Lower Mekong Cooperation with the United States, and has actively participated in the "One Decade of Green Mekong" initiative in Mekong-Japan cooperation. Some countries outside the basin, such as the United States, Japan, India, Korea, India and international organizations such as the World Bank and the Asian Development Bank, have significant influence on basin governance. Social participation in Lancang-Mekong River Basin governance plays a very important role. A variety of stakeholders, ranging from global network initiatives to local NGOs, from business enterprises to communities, have been actively engaging in the governance of the Lancang-Mekong River Basin. They have adopted different strategies (e.g., scientific research, capability building, policy advocacy, and citizen engagement) to exert influence on various issues such as climate change, biodiversity, hydropower development, and sustainable livelihood, revealing overlapping and interacting mechanisms of participation. The future trend of basin cooperation is more optimistic along with the consensus strengthening and capacity building, although there may be still some interferent brought by big power competition and interest disputations.

9.1 Introduction of Integrated River Basin Governance (IRBG)

This section emphasizes the main challenges faced by implementation and functioning of water governance. It provides the scientific definitions of water governance as well as its principles.

9.1.1 Definition of Integrated River Basin Governance (IRBG)

As IRBM has been defined as IWRM taking basin as the management unit in a previous chapter, IRBG can be coarsely defined as integrated river basin water governance (IWRG) taking basin as the unit. So we firstly discuss the definition of water governance.

There is a clear opinion among many scholars that in order to improve water resources management, it is necessary, first of all, to create a solid water governance platform. It should define the rules of the game in water management and create an appropriate environment and prerequisites for it. In other words, water resources management will be ineffective in the absence or in case of inadequate water governance.

While looking for a definition of water governance, the literature mainly refers to the three sources listed below.

- The OECD defines water governance as the "*range of political, institutional and administrative rules, practices and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision makers are held accountable for water management*" (OECD, 2015).
- The term water governance encompasses "*the political, economic and social processes and institutions by which governments, civil society, and the private sector make decisions about how best to use, develop and manage water resources*".
- GWP defines water governance as "*the set of political, social, economic and administrative systems in place to regulate the development and management of water resources and provide water services at different levels of society*" (GWP, 2004)

Despite the slight difference in definitions, it is important to keep in mind that water governance must follow certain principles. The main principle is to achieve equal and sustainable water supply for the entire society, economy and nature, elimination of "water inequality, water shortage and water hunger" through water resources use. Thus, the target basis of water governance should be overcoming hydroegoism in all its manifestations (Dukhovny & Ziganshina, 2010).

Neither in science nor in practice is there a definite rigid approach to the framework of water governance. Each region, country, basin or sub-basin is unique. This means that approaches to water governance must be adapted to each of these levels.

Generalising the principles of water governance we can refer to the OECD methodology (OECD, 2015). The authors base their principles on three complementary aspects of water governance:

(i) effectiveness—contribution of the governance to define the clear sustainable goals and objectives at all its levels, for implementation of these political goals and achievement of expected results.
(ii) efficiency—governance's contribution to maximising the benefits of sustainable water management and welfare at the lowest cost to society.
(iii) trust and engagement—involves contribution of governance to building public confidence and ensuring stakeholders' participation.

Effectiveness includes correctly chosen levels for the implementation of water governance principles, as well as policy coherence and capacity. Efficiency includes the collection, processing, sharing and distribution of data and information, as well as funding and regulatory frameworks. Finally, trust and engagement includes, but is not limited to, monitoring and evaluation, trade-offs and cooperation among users and economies, broad stakeholder engagement, and transparency to demonstrate performance.

Water governance can make a significant contribution to the design, implementation and following of appropriate policies for the economic, social and environmental benefits of water use. Establishing the responsibility of different levels of government, civil society, private sector and a wide range of stakeholders will increase their responsibility in the governance and management of water resources.

Integrated River Basin Governance focuses on the social, economic, organisational and institutional arrangements of river basin management (Hooper, 2005). As we understand it, Integrated River Basin Governance is the implementation of water governance within a basin, emphasising the integration of all aspects of water governance. Integrated River Basin Governance cooperation refers to the cross-border cooperation of various entities in the watershed for better water governance and obtaining more shareable benefits. It takes water as the centre, but sometimes it may go beyond the scope of water and only indicate the cooperation taking place within a river basin.

9.1.2 Integrated River Basin Governance by Basin Community

There has been a shift in policy rhetoric towards adopting polycentric bottom-up community-based approaches, in contrast to centralised top-down approaches (Tantoh et al., 2018). However, in this chapter community is not taken only as a root level organisation or crowd, but as the aggregation of all people and organisations within the basin who share the same basin and link their destiny together, including root villages. Integrated River Basin Governance by basin community means that all people and organisations should have the opportunity and methods to participate in water governance within the basin in which they are involved. It's rational to see basin community as a complex system of formal and informal organisations or groups of people in different level, which can also be seen as sub-communities that constitute the whole basin community.

Basin (sub-)communities are created with different organisational structures, depending on tasks to be solved, legal and administrative systems, availability of human and financial resources. These are usually, but not always, formal legal structures. However, in some cases, less formalised structures also can work. Having any organisational structure, basin communities should remain public sector organisations, since water resources management is a public domain (GWP, 2009).

Often, the official basin communities are part of the public sector, but effective IRBG also requires broad participation of various stakeholders, which can be represented by community groups, economic sectors, nongovernmental organisations and private enterprises (Dukhovny & De Schutter, 2018).

In fact, basin communities are bodies combining a number of structures necessary for Integrated River Basin Governance. They are called upon to play a leading role in solving water governance problems at the basin level. This means maintaining full awareness and participation of decision makers and actors from all economic sectors and at all levels of both the public and private sectors.

Basin communities perform many tasks, but there is a tendency to group them into three key functions (Table 9.1). Depending on the purpose for which the basin community was created and its managerial structure, it can perform one, several or all of these functions.

9.1.3 The Outcomes of Integrated River Basin Governance Cooperation

In recent years, Basin countries have taken progressive steps towards a common future with an emphasis on water resources management and governance. Water security is the core of such cooperation and is designed to protect two important principles. First, water cooperation should not jeopardise a country's sovereignty. Secondly, the economic and social development of any country should not be sacrificed for the use of water by another countries (Xing, 2017).

Regional and/or sub-regional cooperation has the potential to enhance the political, diplomatic, economic and cultural influence of riparian countries. Therefore, cooperation in developing national strengths and ensuring the safety of transboundary waters is in the interests of all Basin countries (Ponte, 2012).

An important goal of basin water governance cooperation is to resolve conflicts of national interests. Each country focuses on the use of river water in different ways: China and Laos focus on hydropower; Thailand and Vietnam highlight the importance of water use in agriculture; Cambodia focuses on the fishing industry. In addition, China, Laos, Myanmar and Thailand need water transport. Cooperation in the field of water governance includes all six countries and will align the interests of each country and resolve disputes on one platform (Van Thang et al., 2019).

The basin countries, through cooperation in the field of water management and water governance, have made tremendous efforts to combat river pollution. The overall water quality of the Mekong River is relatively satisfactory and meets the agreed minimum standards. Moreover, water quality indicators are fairly stable, with rare exceptions in the densely populated delta (MRC, 2020).

Also, due to close cooperation in water governance, it was possible to achieve an increase in releases from reservoirs during the dry season. On the one hand, this is not beneficial for upstream countries with hydroelectricity Plants (HEPs), but on the

Table 9.1 Key functions of basin communities

Key function	Sub functions	Concrete tasks
Research, monitoring, coordination and regulation	Data collection	Collection, management and sharing of data on water resources availability and their use
	Prevention, monitoring and strengthening	Monitoring and control of water pollution, mineralisation levels, etc. Strengthening relevant laws and regulations to prevent degradation of natural resources and restore ecosystems
	Coordination	Harmonisation of policies and actions in the basin by governmental and non-governmental organisations
	Conflicts' resolution	Providing mechanisms for negotiation and litigation
Planning and financing	Water distribution	Determination of mechanisms and criteria for water resources distribution between water-user industries
	Planning	Preparation of medium and long term plans for water resources development and management in the basin
	Resources mobilisation	Funding providing (for example, through collection of water charges or water tax)
Development and management	Construction, operation and management	Design, construction, operation and maintenance of water infrastructure. Guaranteeing and enforcing coherent water resources management
	Combating water hazards	Development of protective mechanisms and protective actions against floods. Conducting emergency response work, developing plans for dealing with droughts and floods
	Ecosystems' protecting and preserving	Prioritisation and implementation of measures to protect ecosystems, including awareness raising campaigns

Source Adopted and modified from GWP (2009) other hand, it is beneficial for downstream countries to combat drought. This balance is a mutual benefit of basin cooperation in the field of water governance.

An excellent example of water governance cooperation is the fact that agriculture and fisheries in Vietnam, Laos and Thailand were severely affected by the drought in 2015–2016. Moreover, there has been a significant intrusion of seawater into groundwater in Vietnam. An analysis report from Vietnam has got the conclusion that the main causes of the drought are the occurrence of El Nino in 2015 which caused severe climate draught in this basin and the water use in Thailand, Cambodia and Laos which contributed at least 49% of low season discharge decrease.[1] During this period, China released water to help its lower basin neighbours at their request (Gruenwald, 2020). China released an emergency water supply from its Jinghong Hydropower Station in the southwest Yunnan province to feed the downstream Mekong River between March 15 and April 10. These timely efforts have helped alleviate drought downstream and have demonstrated the positive impact of upstream dam construction. Vietnamese officials have officially acknowledged the role of the release of water from China's upstream reservoirs in alleviating the drought in Vietnam (Vietnam News Agency, 2016).

The commitment to continuous monitoring as part of water governance confirms the expected impacts of increased flow resulting from the construction of new reservoirs and HEPs in the Basin. This redistribution of seasonal flows from the wet season to the dry season by existing and planned HEPs could provide additional dry season flows to meet some of the planned water needs in downstream countries (Xing, 2017).

However, it is necessary to be extremely careful, in view of the fact that uncoordinated operation of reservoirs can cause negative consequences. This could be a delay in the onset of flooding due to dam filling and unexpected flow changes during the dry season, which would negatively affect the downstream countries and the delta.

Moreover, water governance in transboundary basins as a non-traditional security issue is closely intertwined with traditional security management. All Basin countries are developing economies. They are heavily dependent on the agricultural sector, where water demand is constantly growing. Consequently, inappropriate water governance and management of water resources can jeopardise national security (Goh, 2004). Under certain unfavourable circumstances, external migration, driven by a change in the volume of river water, can sharply increase. Declining quality and quantity of water resources, population growth and unequal access to them can negatively affect some population groups, exacerbating other problems: a lack of arable land, water, forests and fish (Goh, 2004). In turn, this reduces the economic activity of local population which leads to economic recession in countries and the entire region. The victims may migrate or be expelled to other areas and countries. External migration often provokes ethnic conflicts, riots and uprisings in rural areas. In developing countries, migration and declining productivity can ultimately undermine government control and enable elites to challenge central government (Xing,

[1] https://www.mard.gov.vn/_CONTROLS/ESPORTAL/PubAnPhamTTChiTiet/Service.svc/download/L0FuUGhhbVRUL0xpc3RzL0FuUGhhbVRU/270.

2017). Thus, the proper water governance is intended to provide an ideal platform for the coordination of transboundary water resources, which can indirectly enhance comprehensive security in the region.

9.2 International Cooperation Mechanisms in the Lancang-Mekong River Basin [Shaofeng Jia, Hoaithuong Do, Boris Gojenko]

Because water cooperation is only one part within the whole system of international cooperation, and there are very little special agreement or mechanism for water cooperation, and water is always treated as one factor within bi/multi-lateral cooperation agreement or mechanism, it's rational to put water cooperation under the umbrella of reginal cooperation, or understand water cooperation through the lens of regional cooperation.

9.2.1 Cooperation Mechanisms That Have Emerged

The cooperation mechanism means the matching and integration of institutions of two or more groups to achieve effective collaboration.

The vision of better management of the Mekong River brings certain cooperative advantages for the trade development of riparian countries (Zhu, 2010). A series of sub-regional cooperation mechanisms in the Mekong River has been established since the 1990s. At present, there are about 15 cooperative mechanisms in the Mekong Region divided into two groups: intra-regional mechanisms (cooperation among Mekong countries) and between Mekong countries with partners outside the basin (Le, 2018). This section introduces the 7 most important river basin cooperation institutions and their cooperation mechanisms in chronological order of their establishment (Table 9.2).

– **The Mekong River Commission**: In 1957, the International Mekong River Committee was established by the United Nations with four countries Thailand, Laos, Cambodia, and the Republic of Vietnam to jointly exploit the Mekong River (Backer Bruzelius, 2007). However, because of the war, the exploitation plan stalled. On 5/4/1995, the Mekong River Commission (Mekong River Commission) was established with 4 members, namely Laos, Cambodia, Thailand, and Vietnam, established with the signing of the "Agreement on cooperation for sustainable development of the Mekong River. The main objective of the Mekong River Commission is to promote cooperation among riparian countries in the sustainable use, development, and protection of water and related resources and for the mutual benefit of the countries (Backer Bruzelius, 2007). China and Myanmar joined as dialogue partners.

Table 9.2 The Mekong River riparian country cooperation mechanism

No.	Cooperation organisations	Country members	Established date
1	Mekong River Commission (MRC)	– Thailand, Laos, Cambodia, Vietnam – China, Myanmar (dialogue partner)	1957 (April 1995 reorganised)
2	Greater Mekong Subregion (GMS)	Myanmar, Laos, Thailand, Cambodia, Vietnam, and two provinces of China (Yunnan, Guangxi)	1992
3	ASEAN-Mekong Basin Development Cooperation (AMBDC)	ASEAN countries and China	1995
4	Ayeyarwady-Chao Phraya-Mekong Economic cooperation strategy (ACMECS)	Cambodia, Laos, Myanmar, Thailand, and Vietnam	November 2003
5	Cambodia, Laos, Myanmar, and Vietnam Cooperation (CLMV)	Cambodia, Laos, Myanmar, and Vietnam	November 2004
6	Cambodia-Laos-Vietnam Development Triangle (CLV)	Cambodia, Laos, and Vietnam	November 2004
7	Lancang–Mekong Cooperation (LMC)	China, Thailand, Myanmar, Laos, Cambodia, Vietnam	2014

Source Author's compilation

According to Dore (2003), Laos and Cambodia are the two countries with the highest proportion of territories linked to the Mekong River (97% and 86%, respectively). Therefore, the cooperation of the Mekong sub-region countries for these two countries is considered to have a direct and serious impact on the life and development of these countries compared to other members of the regime. Besides, Vietnam is a country located at the end of the Mekong River basin, the gateway to important traffic routes in the basin. For Vietnam the Mekong accounts for about 25% of the country's territorial area and 35% of the country's population, this region has strategic implications for the socio-economic development, environment, and national security of Vietnam. Participation in the Mekong River Commission is an important strategy to promote the development of this country in exchange and trade with countries in the region and around the world (Nguyen, 2015). On November 26, 2020, the International Mekong River Commission held the 27th session of the Council in conjunction with the 25th session with Development Partners, in Laos. At this meeting, the Council approved many important documents of the Commission such as a basin-wide environmental management strategy for important ecological environmental values; the Committee for the 2021–2030 River Basin Development Strategy, and the Commission's Strategic Plan for the period of 2021–2025; Working Program of the Commission for the year 2021–2022; Master Plan on Water Traffic. In addition, the meeting also discussed with the Dialogue Partners and Development Partners, the situation of cooperation and developments of water resources in the basin, the Common Environmental Monitoring Program for the above hydropower projects in mainstream Mekong River, and the response to extreme weather in 2020 and may continue to happen next year. The representatives of the donors, in addition to welcoming the Commission's cooperative achievements including the Commission's Joint Statement on Mekong mainstream hydropower projects, paid special attention to promote the establishment of monitoring systems for these projects and make them publicly available to support stakeholder consultation sessions.

After 25 years, the Mekong River Commission has achieved many positive results, contributing to promoting development in member countries, enhancing cooperation among member countries, and expanding cooperation with two upstream countries (Chinaand Myanmar) and many other international partners. In the Mekong basin cooperation frameworks, the Commission is the only organisation that has the function of developing legal frameworks, including binding regulations for member states to publicly and equally share water resources, jointly protect the river basin's ecological environment, as well as to promote joint development projects. The Commission's activities are not only important for economic and social development, and environmental protection but also contribute to strengthening friendly relations between countries in the region.

– **Greater Mekong Subregion cooperation**: The Greater Mekong Subregion was established in 1992 and includes five countries belonging to the Association of Southeast Asian Nations (ASEAN), namely Myanmar, Laos, Thailand, Cambodia, Vietnam, and two provinces of China (Yunnan, Guangxi). This is a region with great economic potential with rich natural resources, especially the resources in agriculture—forestry, fisheries, hydropower, and waterway transportation (Duong et al., 2020).

The Greater Mekong Subregion programme is considered to be the most complete and effective sub-regional cooperation mechanism, with priority given to infrastructure development, energy, telecommunications, tourism, trade investment, and resource development, human resources, and the environment. The Greater Mekong Subregion Program strategy adopts three pillars:

1. Enhancing connectivity through sustainable infrastructure development and converting transport corridors into transnational economic corridors;
2. Improving competitiveness through efficient support for cross-border passenger and cargo transportation, market integration, production processes, and value chains;
3. Raising public awareness through programmes and projects to address common social and environmental concerns (also known as 3C: Connectivity (infrastructure connectivity), Competitiveness (enhancing capacity), Community (community connection) (ADB, 2012).

Initiatives and activities in the Greater Mekong Sub-region programme focus on 9 main areas including transport, energy, environment, tourism, posts, and telecommunications, trade, investment, human resource development, agriculture, and rural development. 11 priority programmes have been identified in the sub-regional economic cooperation framework, including (i) Posts, telecommunications and information and communication technologies; (ii) North-South economic corridor; (iii) East-West economic corridor; (iv) Southern Economic Corridor; (v) Regional electricity and electricity trade links; (vi) Framework of environmental strategy; (vii) Facilitating cross-border trade and investment; (viii) Strengthening private sector participation and competitiveness; (ix) Developing human resources and skills; (x) Water resource management and flood prevention; (xii) Greater Mekong Subregion sub-region tourism development (ADB, 2012).

Greater Mekong Subregion cooperation is recognised by many experts as one of the fastest-growing regional cooperation channels in the world. During 1992–2006 all Greater Mekong Subregion countries experienced significant economic growth, among these the less developed countries generally experienced higher rates of growth than the more developed ones. Starting in 1992 with an average of US$664, the average GDP per capita (excluding China) increased to US$1,042 in 2006. From 1992 to 2006, Myanmar and Vietnam increased 171% and 129%, respectively, in GDP per capita. And thereafter to now, the economic growth rate of this region has maintained higher than the average of the world. In line with economic improvement, Greater Mekong Subregion countries achieved better quality of life for people in the subregion, heading towards high-quality development (Duong et al., 2020). This is one of the factors that together with abundant natural resources has become an attractive force for international investors. Therefore, Greater Mekong Subregion Greater Mekong Subregion cooperation is an important mean for all the regional countries, bringing common interests in many aspects such as security, politics, economy, culture—society, and improving the position of each country in the region and the international arena.

– **Ayeyarwady-Chao Phraya-Mekong Economic Cooperation Strategy**: The Ayeyarwady-Chao Phraya-Mekong Economic cooperation strategy (ACMECS) is an economic cooperation framework consisting of five countries (Cambodia, Laos, Myanmar, Thailand, and Vietnam) to strengthen mutual and economic cooperation, to exploit and promote comparative advantage among regions and member countries, to improve competitiveness and narrow the development gap (De et al., 2020). ACMECS was established in November 2003 at the Bagan Summit after a proposal by Thailand. So far, ACMECS has seven areas of cooperation including: (i) trade-investment; (ii) agriculture; (iii) industry—energy; (iv) traffic; (v) travel; and (vi) human resource development; (vii) health. ACMECS established seven Working Groups corresponding to 7 areas of cooperation. Each ACMECS country coordinates at least 1 field of cooperation: Thailand coordinates trade investment and health; Vietnam coordinates human resource development and industry-energy; Cambodia coordinates tourism cooperation; Laos coordinates traffic cooperation; and Myanmar coordinates agriculture (De et al., 2020). The ACMECS Summit is held every two years in each country in rotation, and a Ministerial Meeting takes place annually. The ACMECS is a more effective forum than others because of the opportunities for regular negotiation amongst high-ranking officers and governments.

Most recently, the 9th ACMECS Summit, took placeonline in December 2020, with the presence of senior leaders of Cambodia, Laos, Myanmar, Thailand, and the ASEAN Secretary-General. With the theme "Partnerships for Connectivity and Recovery", ACMECS focused on reviewing the implementation of the Bangkok Declaration and the ACMECS Master Plan for the period 2019–2023 adopted by the leaders. In regard of future cooperation, leaders stated that the region and the world were facing unprecedented challenges due to the effects of the Covid-19 pandemic and non-traditional security issues such as climate change, environmental degradation, natural disaster, floods, etc. Leaders expressed concern about severe droughts, especially in 2019 and 2020, causing the water level of the Mekong River to drop. New record low and disrupted food supplies affected the subregion's ecosystem, agriculture, and aquaculture. On that basis, the leaders affirmed their determination to:

1. Promote cooperation in environmental protection, smart agricultural development and sustainable management of water resources in the Mekong River, disaster management and climate change;
2. Strengthen efforts to both prevent, combat and respond to the Covid-19 pandemic and economic reconstruction;
3. Restore supply chains by promoting trade, investment, industry, tourism, digital economy development, e-commerce, and human resource development among member countries of ACMECS;
4. Promote the participation and contribution of development partners, international organisations and the private sector in the implementation of the three pillars of cooperation of the ACMECS Master Plan and soon put the ACMECS Development Fund into operation to effectively implement priority projects;
5. Ensure the connectivity and resonance between ACMECS cooperation with ASEAN and related sub-regional cooperation mechanisms, at the same time consider improving the structure and operating modes of ACMECS cooperation towards enhancing efficiency and development maximise resources.

– **Cooperation in Cambodia, Laos, Myanmar, and Vietnam (CLMV)**: At the ASEAN-Japan Summit, in December 2003, Tokyo, Japan, senior leaders of Cambodia, Laos, Myanmar, and Vietnam (CLMV) agreed to hold the first CLMV Summit on the occasion of the 10th ASEAN Summit, in November 2004 in Vientiane, Laos. The meeting adopted the "Vientiane Declaration" on "Strengthening economic cooperation and integration among CLMV countries" (Austria, 2004). The Vientiane Declaration affirmed the CLMV's determination to boost economic cooperation with each other and integrate into the Mekong, ASEAN, and regional cooperation frameworks. At the same time, it called on countries and international organisations to increase support for the four countries to narrow the development gap (Sotharith, 2008).

Areas of cooperation in the CLMV framework include trade, investment, agriculture, industry, transport, tourism, and human resource development. CLMV encourages participation from the private sector and businesses across countries. CLMV currently has 7 specialised working groups coordinated by member countries, specifically, Vietnam coordinates the working group on trade investment, information technology, and human resource development; Cambodia coordinates the tourism working group; Laos coordinates the transport working group; Myanmar coordinates the agriculture and industry-energy, working group (Sotharith, 2008). In recent years, the countries in CLMV have had strategies to promote diplomatic relations with countries inside and outside the region such as Thailand, China, Japan, and Korea. Among these countries, Thailand is one of the countries that takes the lead in promoting trade, building capacity, especially in enhancing productivity and encouraging private sector participation. Also, Thailand and the CLMV countries are members of ACMECS as well as the Greater Mekong Subregion, so there is always a close link in both economy and society between these countries. China, Japan, and Korea are the most important partners to help bring CLMV to the next level of development. The increasing volume of trade and investment from these countries will help strengthen CLMV's economy through technology transfer, skill enhancement, job creation, capital mobilisation, and infrastructure improvement (Le, 2018). At the 10th CLMV conference, the leaders of the four-member countries approved three documents including the Joint Declaration of the Conference, the document "CLMV Development Framework" and the cooperation list of 16 priority projects. Which, "CLMV development framework" is a document that guides to building the CLMV region into an international business centre and towards the goal of becoming economies with a high average income in 2030. Leaders of the four countries also agreed to strengthen connectivity in many aspects for the sustainable and inclusive development of the CLMV region in terms of infrastructure, institutions, economics, and people.

– **Cambodia-Laos-Vietnam Development Triangle cooperation**: The Development Triangle Area (CLV) of Vietnam, Laos, and Cambodia was established in 2004 by three Prime Ministers. This organisation includes 10 provinces: Kon Tum, Gia Lai, Dak Lak, and Dac Nong (Vietnam); Sekong, Attapeu, Saravan (Laos); and Stung Treng, Rattanak Kiri, Mondul Kiri (Cambodia). In 2009, the three countries agreed to add Binh Phuoc province (Vietnam), Kratie province (Cambodia), and Champasak province (Laos) to the CLV (Chheang, 2018a, 2018b, 2018c).

The goal of the CLV is to strengthen the solidarity and cooperation of the three countries for socio-economic development, hunger eradication, and poverty reduction, contributing to maintaining the stability and security of the three countries. Cooperation focuses on transport, commerce, electricity, tourism, human resource training, and health. In addition to the High-Level Meetings, the three CLV countries agreed to establish a Joint Coordination Committee, consisting of four sub-committees: the economic sub-committee, the social and environmental sub-committee, the provincial coordination sub-committee, and the security and foreign affairs sub-committee (Chheang, 2018a, 2018b, 2018c). Each country appoints a minister to act as the co-chair of the Committee and a member of the Coordination Committee composed of representatives of the relevant ministries, branches, and provinces in the Triangle. The Joint Coordination Committee meets annually. In 2016, the leaders agreed to strengthen collaboration between CLV-DTA and other regional cooperation mechanisms in the Mekong region, particularly the Mekong-Japan Cooperation.

At the CLV 11th Summit (December 2020), the prime ministers of the three countries affirmed their determination to build a peaceful, stable, sustainable and prosperous CLV development triangle by continuing to expand and enhance their effectiveness of cooperation, promoting integration, restructuring the economy, improving the business environment, and closely coordinating with other ASEAN member countries to realise the ASEAN Community Vision 2025. Three prime ministers approved the Joint Declaration on CLV Development Triangle Area Cooperation.

– **The ASEAN Mekong Basin Development Cooperation (AMBDC)**: the AMBDC was established by the ASEAN Summit in 1995 to strengthen ASEAN's linkage to Greater Mekong Subregion cooperation. The main purpose of the cooperation is the development of infrastructure and human capital in the sub-region and the sharing of the resource base between ASEAN Member States and Mekong riparian countries, along with China, while promoting inclusive and equitable growth in the region (ASEAN, 2013). The main axis is a railway corridor from Singapore to Kunming, Yunnan crossing the Malaysian Peninsula, Thailand and Laos, branching to Cambodia and Myanmar (Le, 2018).

AMBDC's main activities are aimed at: (i) economically sustainable development of the Lancang-Mekong River Basin, (ii) dialogue to ensure economic partnership for mutual benefit; and (iii) strengthening the cultural and economic relations between the ASEAN countries and the Basin countries.

The main principles of cooperation in frame of AMBDC are as follows:

(1) supporting and aligning national and generalised development plans for the Basin countries;
(2) achieving direct benefits for people living and operating in the basin, namely: providing new jobs, increased incomes, development of social programmes and hence the raising of living standards.
(3) using the full potential of all resources to ensure stable and sustainable development to improve the management of natural resources and conservation and protection of environment;
(4) complementing projects and cooperation initiatives currently being undertaken by MRC, ASEAN, donor countries, and international organisations and unions.
(5) mobilising the private sector in the implementation of joint projects and activities.
(6) opening participation to all interested countries, as well as regional agencies and international development agencies, to attract additional financial, institutional and technological assistance.

The AMBDC countries have also identified the main priority areas of activity:

1. development of transport infrastructure
2. development of telecommunications and information security
3. development of irrigation networks
4. energy development
5. development of trade and investment
6. development of agricultural sector to saturate domestic consumption, as well as the development of agricultural products export
7. development of forest and mineral resources sustainable use
8. industrial development
9. development of scientific and technical cooperation
10. development of human resources and their training.

The flagship project in the AMBDC—the Singapore-Kunming Rail Link (SKRL) is a pan-Asian high-speed railway network being developed to connect the countries of Cambodia, Laos, Malaysia, Myanmar, China, Singapore, Thailand, and Vietnam. The 6,617.5 km-long railway network is being developed with an estimated investment of $15 bln, under the AMBDC which was formed to encourage economic integration among the ASEAN countries. The project will link the cities in ASEAN countries with Kunming, the capital city of China's Yunnan Province.

Proposed under China's Belt and Road Initiative (BRI), the railway network aims to connect countries to encourage cross-border passenger/cargo transportation and tourism between the countries (ASEAN, 2013).

– **Lancang-Mekong Cooperation (LMC)**: Thailand first proposed the Mekong-Lancang cooperation in 2012 with the participation of six riparian countries: Vietnam, Cambodia, Laos, Myanmar, Thailand, and China. In March 2016, the LMC was formally established at the First LMC Leaders' Meeting in Sanya, China. The LMC mechanism not only supports economic development but also strengthens security cooperation (Biba, 2018). China has pledged $300 million to the LMC Special Fund to support the 1st five-year plan. The LMC has proven its dynamic development by forming a working mechanism from senior to specialised working groups and implementing projects in the field in member countries. The LMC has maintained the mechanism of two-yearly high-level meetings, annual ministerial meetings, SOM meetings, and working groups. The six-member countries agreed to establish five cooperation centres, including the Water Resources Cooperation Center, the Environment Cooperation Center, the Agricultural Cooperation Center, the Center for Exchange Cooperation, and the Career Training Center.

Countries promote academic exchanges through the establishment of the Center for Global Studies on the Mekong. At the 2nd Lancang–Mekong Summit in 2018, countries agreed to approve the Action Plan 2018–2022 with specific cooperation contents on each pillar. So far, LMC has deployed more than 400 projects using the LMC Special Fund. The working mechanisms of LMC have gradually come into operation, initially formulating and implementing action plans (Le, 2018). As a more recent mechanism, the LMC has appropriately pursued a concerted effort with other mechanisms. In December 2019, the Lancang-Mekong Water Resources Cooperation Center signed a Cooperation Agreement with the MRC Secretariat. This is the first cooperation agreement between the LMC and another cooperation mechanism. The agreement set out some key areas of cooperation such as data and information exchange, basin-wide monitoring, and joint assessment of water and related resources. At the 5th LMC Ministerial Meeting in Vientiane (Laos) in February 2020, the Ministers proposed the upcoming LMC priorities including (i) Accelerating the development and implementation of action plans on regional connectivity, production capacity, water resources, commerce, agriculture; strengthen cooperation in response to natural disasters, epidemics and cross-border crimes; (ii) Promoting exchanges and dialogues between local authorities and border gate authorities; and (iii) Improving the operational efficiency of the LMC Special Fund. The LMC will also strengthen the cohesion and complementarity of the LMC with relevant regional cooperation mechanisms.

It can be said that China has seized the initiative from international donors and has invited all the countries of the Mekong Basin to participate in the Lancang-Mekong Cooperation Mechanism (LMC), which is part of the One Belt One Road Initiative, and is designed to support regional integration. Water resources management, although it was the initial unifying theme, has faded into the background, giving way to the issues of establishing development funds, creating infrastructure, facilitating cross-border trade, etc. China has promised $10 billion in loans to partner countries for joint MSLM projects (Simonov, 2018).

As an integral part of the twenty-first century Maritime Silk Road, the LMC performs important functions and tasks for the construction of the China-Indochina economic corridor. China boasts rich experience and remarkable achievements in the construction of hydropower infrastructure. With the development of the BRI, the interconnection between China and the Mekong countries can be significantly improved through the construction of unobstructed land–water transport channels, cross-border power supply networks and power transmission routes. In this way, the management of the Lankang-Mekong water resources can further strengthen the security ties between China and the Mekong countries, which in turn will contribute to the implementation of the Belt Road Initiative.

Common security has become a key element of water resources management through LMC. The Mekong countries are less developed economically than China. However, all six coastal countries share common interests in disaster management and thus must work together to address the security dilemma. As long as the countries concerned follow the path of building mutual trust and cooperation, upstream dams can help regulate the flow of water downstream. By looking for common interests, the LMC attempts to define the roles of all riparian countries. As a result, agreement is possible through mutual understanding (Paramonov, 2018).

Additionally, sustainable security is the ultimate goal of LMC. It is noteworthy that all riparian countries have established principles of ecological and biological protection in their laws and regulations concerning water resources. China, in particular, prioritizes green development in its nationwide planning, and has applied this idea to the management of the Lancang-Mekong water resources to make a new contribution to global environmental security.

In short, the LMC is designed to promote sustainable water security for all riparian countries and promote water cooperation in an environmentally friendly and open way (Xing, 2017).

China, together with the Mekong countries, has established a water security cooperation centre where all riparian countries can share relevant technology and information, and jointly build disaster management capacities.

Finally, the Lancang-Mekong Water Resources Cooperation Center (LMWRCC) was established in Beijing in 2017. It serves as a platform for LMC countries to strengthen comprehensive cooperation in technical exchanges, capacity building, drought and flood management, data and information sharing, conducting joint research and analysis related to water resources. LMWRCC has been supporting the joint working group on various activities such as technical exchanges, capacity building and cooperative projects (LMC, 2018).

The Mekong Delta has great potential for rapid development, but the region also needs to cope with significant security and development challenges, especially environmental degradation, water resources and climate change. In such an environment, cooperation in the Basin can play an important role in enhancing sustainable development in the Mekong subregion, strengthening good-neighbourliness between all the states, assisting countries to implement the 2030 Agenda and further deepening the ASEAN-China strategic partnership (Hong, 2018).

At the first summit of LMC, which took place in March 2016, participants agreed on major areas of this active cooperation. Since then positive results have been obtained. Countries have established mechanisms for dialogue from summit to ministerial meeting and meeting of senior officials. In addition to the centres for cooperation in the use of water resources and cooperation for environmental protection in the Basin, a global centre for the study of the Mekong River was established. Projects are also being implemented: the Forum for Women's Cooperation, the Forum for Cooperation of Tourist Cities in the Basin, and the Lancang-Mekong Special Cooperation Fund.

In order to develop all the available potential, it is necessary to develop a more effective approach for LMC, to identify the exact directions that will bring real benefits and at the same time harmoniously promote other existing mechanisms and frameworks of cooperation. It should also attach great importance to the scientific and sustainable management and use of the water resources of the Mekong River, enhance economic integration in the region, cooperate in the sustainable development of agricultural production, and create favorable conditions for the development of cross-border trade, investment and tourism (Hong, 2018).

The main goal pursued by China in implementing the LMC is to promote more efficient management of the transboundary river basin, as well as to use the geographical proximity, cultural proximity and economic complementarity of all six countries of the Basin.

9.2.2 The Role of Basin Cooperation Mechanism

The cooperation mechanisms serve as platforms for conducting water diplomacy, as they fulfil the roles of policy dialogue facilitator and coordinator, norm builder, and information hub for transboundary water resources management (Phoumin, 2020). From MRC through Lower Mekong Initiative (LMI), the Mekong–Japan Cooperation and Mekong–Republic of Korea Cooperation, to LMC, all these mechanisms consider water security as a significant focus. Their joint statements, issued at high-level conferences, often demonstrate the significance of water cooperation. In 2018, at the 11th LMI Ministerial Meeting, member countries approved restructuring the mechanism into two mainstays of cooperation. Cooperation on water, energy, food, and the environment is of a priority.

Moreover, the 1st LMI Policy Dialogue and the Friends of the Lower Mekong have served as a consultative platform about transboundary water management, in which participants focus on the exchange of water data and ways of employing big data technology to predict droughts and floods in the subregion (MFA, 2019). In the LMC framework, in response to requests from other partners for strengthening subregional cooperation in data sharing, China has proposed projects including the Lancang–Mekong River Space Information Cooperation Center and the Building of a Comprehensive Information Platform for the Lancang–Mekong Water Resources Cooperation (Phoumin, 2020). This has also drawn attention from external partners. Also, according to Phoumin (2020), the US, within the framework of the LMI, established the Mekong Water Data Initiative, a programme of the Sustainable Infrastructure Partnership, and put into operation 'Mekong Water' to support the MRC and promote data sharing for disaster forecasting and policy making. On this basis, downstream countries can publish a new data-sharing platform and a new impact assessment programme in the Lower Mekong. Moreover, the US intends to cooperate with the Republic of Korea to implement a project on using satellite images to assess floods and drought in the Mekong River; and collaborate with experts from the World Bank, Australia, France, and Japan to conduct dam safety assessments on 55 dams in the Lao PDR (Thu & Tu, 2019).

9.3 Perspectives of Riparian Countries on Basin Cooperation and Impact of Countries Outside the River Basin [Hoaithuong Do]

9.3.1 Perspectives of Riparian Countries on Basin Cooperation

Each member country has its opinion of the basin governance cooperation mechanism.

Cambodia is the only basin country with a large portion of the territory within the regime. Therefore, the development direction of the Mekong basin is considered to have a more direct and severe impact on the well-being of the country compared to other countries. This makes Cambodia more eager to join regional cooperation mechanisms such as the MRC, Greater Mekong Subregion (Greater Mekong Subregion), and LMC (Lancang-Mekong Cooperation). From very early on, Cambodia engaged in MRC cooperation and viewed the mechanism stricter than other members. However, past incidents (such as the Yali incident) have disappointed Cambodia with what the MRC has achieved for it. This was improved after a new CEO of MRC took office, but Cambodia's participation in the mechanism was still limited (Backer Bruzelius, 2007).

The Cambodian Government has signed several international environmental conventions related to watershed management, including the Convention on Biological Diversity, the Convention on Climate Change, and the Convention on Wetlands of International Importance. To meet the requirements of these conventions, the Government of Cambodia has assigned some key ministries for the translation of these conventions into national policies (Bunnara et al., 2004). In the newly emerging institutional landscape, several institutions were competing for significant roles in managing natural resources and related issues (Sato et al., 2011). To make institutions more effective regarding basin and watershed management, Cambodia improved its governance and reduced corruption and vested interests in all sectors and at all levels of government to allow more effective law enforcement and allocation of resources; generated a better understanding among government officials and the general public concerning natural resource management and watershed management (Kishor & Damania, 2007). Cambodia established the Cambodia Resident Mission (1996) as the primary operational link between the Asian Development Bank and the government, the private sector, civil society organisations, and development partners. The Government of Cambodia recognises Bank's country partnership strategy for 2014–2018 for Cambodia in line with its significant growth and development plans. It seeks to strengthen the rural–urban linkage towards the goals of human and social development. With the help of Greater Mekong Subregion, the Cambodian government has made significant achievements in areas such as energy, human resources development, telecommunications, tourism, and investigation (GMS, 2018b). As for the LMC, Cambodia contends that it has a political influence on the river basin countries and has the presence of leadership with a clear vision and strong political support from all countries. At the same time, the Cambodian government also believes that the LMC is compatible and complementary to existing regional mechanisms. Cambodia has shown a strong interest in strengthening synergies between the LMC and other regional initiatives such as the Greater Mekong Subregion, MRC, the ASEAN Connectivity Master Plan (MPAC), and the Belt and Road Initiative (BRI) (Chheang, 2018c).

China, as an upstream country, plays an essential role in the development of the Mekong subregion cooperation. Since the MRC mechanism and subsequently the GMS were established, China has maintained a positive attitude in coordinating cooperation with riparian countries in the basin (Backer Bruzelius, 2007; Zhu, 2010).

China participates in multilateral river management institutions, playing a more significant role in its general water governance issues (Biba, 2014). However, cooperation in water resource management for China today is not an easy task. Water issues continue to be tied to national security considerations, and national law restricts the sharing of relevant data. Specifically, sustainable water resource management is considered one of LMC's official documents; they also believe that the LMC will be a key mechanism for economic development through connecting and enhancing the production capacity and managing water resources efficiently (Biba, 2018).

China's main goals when participating in Greater Mekong Subregion cooperation are to (Zhu, 2010):

- connect by road between southwestern China and the Indochinese peninsula,
- connect markets between southwestern China and Southeast Asia,
- establish mutually beneficial economic relations, strengthen mutual exchanges and economic ties, promote multifaceted economic and technological cooperation,
- realise sustainable development in the sub-region, create job opportunities, increase income, eradicate poverty, promote social progress, and improve people's lives,
- deepen subregional cooperation through dialogue and implementation of joint projects, and build an appropriate international trade and investment climate, promoting peace and development in the sub-region.

Specifically, China paid special attention to developing the North–South Corridor, which includes Yunnan and Guangxi provinces and stretches south in two different areas (Bangkok and Hanoi) (Lee, 2015). Special attention has been given to building roads to improve transport infrastructure for regional trade (Lim, 2008). China has promoted the development of a regional market in the Mekong River basin in recent years.

In 2016, to promote cooperation in the rational use of water resources between riparian countries, a new mechanism-LMC led by China, was established (LMC, 2016). According to Middleton and Allouche (2016), the LMC objective is to foster synergy with the Belt and Road Initiative and utilize the Asian Infrastructure Investment Bank's funding, promoting China's diplomacy through joint development and strengthening regional integration focusing on China. Based on the report of De et al. (2020), China has become a significant trade partner of the Ayeyawady-Chao Phraya-Mekong Economic Cooperation Strategy (ACMECS) and contributed significantly to the development of these countries.

Lao PDR has 97% of territory within the Mekong River Basin with an abundance of unexploited water resources (Dore, 2003). This brings a potential in the future use of the water in the Mekong River Basin and makes this country dependent on the Mekong River regime (Backer Bruzelius, 2007). Previous research has shown that there are signs that the Lao government wants the freedom to develop the Mekong tributaries according to its preferences without having to follow the recommendations of the MRC regime. The weak economy with limited human resources and bureaucracy hampered the efforts of Laotians in this regime. Lao PDR is believed to be in a neutral position towards the regime and has acted accordingly (Backer Bruzelius, 2007). However, in recent years, Lao PDR has gradually integrated regional and international economies due to the favourable foreign policy and diversified the country's market (Leebouapao, 2008). Also, Laos has acceded to the international conventions on biodiversity, desertification, climate change, and CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) and Agenda 21 for sustainable development and environmental protection. Through the Ministry of Agriculture and Forestry, the Lao PDR's Government was committed to a programme of integrated area-based development centred on watersheds and river basins. Many laws, strategies, and decrees supporting integrated watershed management, especially at the national level, have been enunciated (Bunnara et al., 2004). Through the 10-year development strategy to 2025, with a vision to 2030 of Laos, it can be seen that international cooperation through Greater Mekong Sub-region, ASEAN, or LMC mechanisms is highly focused (Nishimura et al., 2016). Laos is actively engaged in water conservancy construction, such as Sayaburi Hydropower Station.

Myanmar is considered an upstream country, contributing only 2% of the total flow to the Mekong River (Dore, 2003). Myanmar has great potential for a large market, abundant natural resources, and a young workforce (Zaw, 2008). Since 1988, the Myanmar government has taken a step towards its outward development strategy, actively cooperating with Asian and international economies (Sotharith, 2008). Joining the MRC mechanism as a dialogue partner, Myanmar is only active to a limited extent in all forms of regional cooperation, but Myanmar's representatives attend the annual dialogue meetings, with the Mekong River Commission. As such, Myanmar seems to play only a minor role in managing the Mekong basin (Backer Bruzelius, 2007). Besides, according to Zaw (2008), Myanmar's participation in ASEAN Free Trade Area (AFTA), ASEAN Economic Community (AEC), Greater Mekong Subregion, and several other regional cooperations is expected to lead Myanmar's development based on its comparative advantage in abundant natural resources and cheap labour. Most of the inflow of foreign investments to Myanmar came from Asian countries (especial ASEAN+3), followed by European countries and the United States (Zaw, 2008). Myanmar leaders are focusing on developing hydroelectricity due to the high energy demand in the region and increasing pressure on Myanmar's water resources (Kattelus et al., 2014; Van Dorp et al., 2018). Although Myanmar has abundant water resources, its spatial and temporal distribution is very uneven, leading to water scarcity and desertification in the arid regions of the central region, problems of flooding and salinity in the Ayeyarwady Plain and flash floods in the north and west of Myanmar. Deforestation caused by illegal logging causes erosion and sedimentation in rivers and reservoirs, a cause of navigation problems (Van Dorp et al., 2018). Inconsistent water management overlaps responsibilities in some sectors, seriously affecting water resources. Water resources are managed in an ad hoc fashion, with no long-term planning leading to little or no policy integration or cooperation. In 2014, the government called for an Integrated Water Resources Management approach to deal with current and future problems that will arise as a direct result of the country's development (NWRC, 2014). In 2019, Myanmar signed a cooperation agreement with the Lancang-Mekong Water Resource Cooperation Center of China on water management. Myanmar expressed confidence when participating in the programme, emphasising that the problem of Mekong River resources cannot be solved by one country alone. In addition, Myanmar also attaches great importance to the LMC's "special fund projects", for the development of the six LMC member states, for example, the Bagan Stupa emergency repairs of Myanmar.

Thailand is a country with one-third (36%) of the territory located in the Mekong River (Dore, 2003), occupying an important position in the management of the Mekong River Basin. Thailand has signed the international conventions on Biodiversity, Climate Change and the Kyoto Protocol, Desertification, Endangered Species, Hazardous Wastes, Marine Life Conservation, Ozone Layer Protection, and Wetlands. Policy regulations relating to watershed management can be traced back to the 1950s. Legal consideration of watershed management in Thailand was adopted in 1975 when the Urban Plan Act 2518 B.E. (1975) was approved by the Thai Parliament (Bunnara et al., 2004). Land-use planning approaches in terms of land development have been promulgated since 1960 to improve and restore agricultural land and environmental conditions (Gyawali et al., 2013). Also, the Cabinet has approved many resolutions aimed at solving complexities related to social, economic, and environmental issues, particularly in upland and highland watersheds. However, according to Backer Bruzelius (2007), Thailand prefers a loosely defined cooperation framework. The country has been accused of unnecessarily delaying the establishment of flow regime regulations. Since Thailand is a fairly advanced country and has a developed economy, it does not need the development resources that the MRC can provide. Thailand also has a more explicit stance on issues such as environmental impact assessment (EIA) regulations, is less concerned with adapting existing procedures to those proposed by the MRC, and does not require their capacity as much as some of the other members. Thailand thinks that some of MRC's policy recommendations and requests from downstream riparians are too strict (Backer Bruzelius, 2007). However, Thailand's remarkable development has made it an important partner as well as an investor with other riparian countries (De et al., 2020). Also, grasping its essential position between India and China, Thailand has taken a wise step in cooperating with these two countries through mechanisms such as the LMC or MGC to promote the economy (Banomyong et al., 2011).

As a downstream country, **Vietnam** is facing the risk of suffering enormous, unforeseen impacts from upstream mainstream development programmes and projects while also holding the gateway to trade of the Mekong countries and the world (Nguyen, 2015). Therefore, Vietnam always pays attention to development cooperation in the Mekong River region. From early on, Vietnam has actively participated in the development of mechanisms, procedures, and programmes of the Mekong River Commission, which is an essential legal basis for water resources and related resources in the river, to protect Vietnam's interests in the Mekong Delta (Nguyen, 2015). Besides, within the framework of the MLC, Vietnam has also promoted cooperation in the management and sustainable use of water resources to achieve a balance of interests and responsibilities among the Mekong riparian states. It can be said that Vietnam is one of the most active and proactive countries in preparing, drafting documents, and discussing at LMC conferences (Le, 2018). Furthermore, under the Greater Mekong Subregion mechanism, Vietnam has been effectively involved in trade and investment facilitation activities, including simplifying customs procedures, facilitating goods, and granting travel rights to vehicles and territories of Greater Mekong Subregion countries (Le, 2018). Vietnam is also an active member of regional organisations such as ACMECS, CLMV (Cambodian, Laos, Myanmar, Viet Nan) and CLV (Cambodian, Laos, Viet Nan) (Chheang, 2018a).

9.3.2 Impact of Countries Outside of the Basin

For a long time, developing countries have sought to reach outside powers to maintain regional order by pursuing security cooperation and deepening economic relations. Regulating the domination of any significant power at the same time creates economic interdependence and benefits from cooperation. However, it seems the countries of Southeast Asia are proactively pursuing the more extensive powers for aid and grace. The effectiveness of this twin strategy depends mainly on the powers allowing what happens. Its success is mainly because these developing states are not seen as a threat to great powers. However, under certain conditions, this one-way property needs to be reconsidered. For now, it seems that regional powers are leading the way. The USA, Japan, South Korea, India and other influential countries are becoming more proactive and expanding their presence and importance in the region. Besides China, four great powers USA, Japan, South Korea and India, took the lead in the new engagement. Although the level of regional involvement differs from country to country, this new round was primarily triggered by China's attempt to establish new institutional rules through the LMC and, more broadly, the BRI. The strategic outcomes of these three countries' diversified moves appear harmonious even though each has its separate policy and mechanism goals. Notably, President Trump's Indo-Pacific policy has added impetus to the re-engagement of powers outside the region into the Mekong sub-region. The USA's presence is an essential factor in the policy setting of significant powers. The USA possesses many advantages not only from military power but also economic and soft power. The USA has extensive security arrangements with most Southeast Asian countries.

– **Mekong–US Cooperation**: The USA, as a superpower after World War II, is an early and significant actor in the Indo-China peninsula. The USA entered the region in 1950s and was the main initiator of the construction of MRC in 1957. In recent years, the USA has become more active in the region.

The LMI mechanism was formed in 2009 under the initiative of the USA. So far, the LMI has been implementing some of the subsequent initiatives and cooperation activities, including the "Mekong Forecast, the Delta Research and Global Observation Network programme, and environmental cooperation to build automatic monitoring stations to control and evaluate climate change effects in the Subregion area (Duong et al., 2020). Also, in 2009, the USA funded some projects in the fields of environment, health care, and education. For example, in the Lower Mekong sub-region, USA provided US$7 million for environmental projects (LE, 2016). In 2010, a Partnership between the Mekong River Commission and the Mississippi River Commission was established to enhance the exchange of experiences and cooperation between the two sides.

In the past, the USA foreign policy in Southeast Asia had a certain contradiction, especially when it came to the Mekong sub-region. However, since introducing the free and open Indo-Pacific strategy (FOIP) in 2018, the region has seen a significant change in the USA's engagement (Parameswaran, 2018). In the FOIP strategy, the LMI has been reinstated as a tool for the USA to reinforce cooperation with the sub-region. At the 10th LMI Ministerial Conference in 2017, then US Secretary of State Rex Tillerson proposed the "Mekong Water Data Initiative" to promote sharing and using the Mekong River system data of the MRC (Thuy, 2020).

In September 2020, the first Mekong-US Ministerial Meeting took place online. The conference was co-chaired by Deputy Prime Minister, Foreign Minister Pham Binh Minh of Vietnam and Permanent Deputy Minister of Foreign Affairs of the United States, Myanmar, Thailand, and the Secretary-General of ASEAN. The conference officially announced the upgrade of bilateral cooperation to the Mekong-US Partnership (MUSP) based on the successes of the LMI mechanism established in 2009. Regarding the direction of the next phase of cooperation, the ministers stated that, given the challenges and opportunities facing the Mekong sub-region, the US-Mekong Partnership should aim to promote peace, stability, and prosperity in the region, supporting the implementation of the Sustainable Development Goals to 2030 and the ASEAN Community Vision 2025. The two sides exchanged principles of cooperation and agreed to focus on four areas: economic connectivity; sustainable management of water resources, natural resources, and environmental protection; non-traditional security; and human resource development. The USA announced that it would spend nearly $153.6 million on cooperation projects in the Mekong region for increasing the sharing of water resources data for policymaking and disaster management (VNA, 2020) (Table 9.3).

– **Mekong–Japan Cooperation**: Japan has played an essential role in the Mekong sub-region, which has undertaken three major initiatives for CLMV since the 1990s. These initiatives were the Forum for Comprehensive Development of Indochina (FCDI) in 1995, the AEM-METI Economic and Industrial Cooperation Committee (AMEICC) established in 1998, and the New Concept of Mekong Region Development announced at the Japan-ASEAN Special Summit in December 2003 (Kraisoraphong, 2017; Pan, 2014; Uchida & Kudo, 2008). The New Concept of Mekong Region Development is a new attempt based on regionwide development. It was included in Japan's Official Development Assistance (ODA) Charter revised in 2003 (Pan, 2014).

The Mekong-Japan Regional Partnership Program since 2007 has formalised Japan's involvement in the entire sub-region and institutionalised annual high-level meetings. At ASEAN Summit 12 (Philippines, January 2007), Japan launched the Japan-Mekong Partnership Program for Shared Prosperity. Subsequently, the first

Table 9.3 Overview of US-Mekong Cooperation

Time	Cooperation actions
1957	The MRC was established under the auspices of the United Nations (UN). MRC is composed of four countries, namely, Thailand, Laos, Cambodia, and Vietnam
1968–1971	The United States and the World Bank (WB) provided funds for Laos to complete the construction of Nam Ngun hydropower dams on a large branch of the Mekong river. This is also the first hydropower dam of Lao PDR to be constructed
July 2009	US Secretary of State launched the LMI as a starting event of the sister-river agreement signed between the Mekong River Commission and the Mississippi River Commission
November 2011	The United States Senate approved Resolution 227, calling on countries to protect the Mekong River Basin by postponing the construction of hydropower dams on the mainstream of the Mekong River
July 2012	US Secretary of State launched the Lower Mekong Initiative 2020 (LMI 2020); Myanmar became the sixth official member of LMI. LMI 2020 marked the United States' multi-year vision and long-term commitment to the Lower Mekong

Source LE (2016)

Mekong-Japan Summit was held in November 2009 in Tokyo, adopting the Tokyo Declaration "A New Partnership for a Commonly Prosperous Future" as the foundation for cooperation in 2009–2012 (Kagami, 2009). The cooperation is implemented in many fields such as socio-economic development, infrastructure construction, implementation of the Millennium Development Goals, environmental protection, and water security in the Mekong River. At the fourth high-level conference (April 2012), leaders of countries approved the Tokyo Strategy as the foundation for cooperation in the period 2013–2015, including three main cooperation pillars: (i) Strengthening connectivity within the Mekong sub-region and between the Mekong sub-region with regions and the world; (ii) Cooperation for mutual development between the Mekong countries and Japan; (iii) Environmental protection and human security. Also, the Mekong-Japan cooperation has been implemented within the Mekong-Japan Economic and Industrial Cooperation Initiative framework, the "Green Mekong decade" Initiative, and cultural exchange, people exchange programmes (Kraisoraphong, 2017).

The 10th Mekong–Japan Summit Meeting in October 2018 adopted the Tokyo Strategy, expressing the determination to cooperate in achieving the Sustainable Development Goals (SDGs) in the Mekong region to fully implement the 2030 Agenda for Sustainable Development (Duong et al., 2020). Also, in 2018, Japan aligned its policy with the US Indo-Pacific strategy (Basu, 2018; Matsumura, 2019). Japan argues that "the Mekong subregion has a geographic interest that can benefit significantly from the realisation of a free and open Indo-Pacific". At a meeting in November 2018, Japanese Prime Minister Abe and the US Vice President agreed to spend $70 billion on infrastructure development in the Indo-Pacific region, especially for power project quality in Southeast Asia. Japan expanded its presence with the USA and supported the ASEAN in the Vision on the Free and Open Indo-Pacific

(FOIP). FOIP demonstrated ASEAN's efforts to foster cooperation among regional partners by advocating inclusiveness, transparency, and law-based regional architecture. Through its support for FOIP, Japan strengthened regional, peaceful and stable connectivity in the Mekong. Tokyo's commitment to the Mekong sub-region was also reflected in Japan's support for existing sub-regional mechanisms such as ACEMCS (Matsumura, 2019).

– **Mekong–Korea Cooperation**: Korea is also becoming more and more active in the Mekong sub-region under President Moon Jae-in's New South Policy (NSP). Mekong-Korea cooperation was implemented with the first Mekong-Korea Ministerial Meeting held from October 27–28, 2011. The meeting adopted the "Declaration of Han River" on the establishment of a "comprehensive partnership between the Mekong countries and Korea for shared prosperity", which defines the goals, principles, and orientations for cooperation in the future between the Mekong countries and South Korea (LE, 2016). In 2012, all parties developed an action plan for this new cooperation mechanism. The priority areas of cooperation were ASEAN connectivity, sustainable development, and human resource development. The NSP represents a strong economic connection between Korea and the sub-region. ASEAN has become Korea's second-largest trading partner, Korea's investment in ASEAN has increased 20 times over two decades, especially for CLMV countries (Kang, 2020). The ASEAN-Korea Summit held in November 2019 in Korea showed a solid commitment to ASEAN and emphasised that the Mekong-Korea Cooperation was the foundation for deepening its commitment. The Mekong-Korea Summit was also held on the sidelines for the first time (since 2011, the mechanism is only at the Ministerial and SOM level), outlining potential areas where Korea could support the areas, including water resources and infrastructure development. At the same time, considering the CLMV's diplomatic relations with North Korea, South Korea also hoped the sub-region can support the peace process on the Korean peninsula (YNA, 2019).

South Korea also expressed its support for the USA's Indo-Pacific Strategy, which Seoul sees as bringing many economic benefits to the country and is consistent with the NSP in the subregion. Korea also supports ACMECS with the criterion that better coordination between the sub-region and external donors in planning will lead to mutual benefits (Kang, 2020).

– **Mekong–Ganga Cooperation (MGC)**: MGC cooperation was established at the initiative of India and Thailand, approved at the meeting between the Foreign Ministers of 6 countries Cambodia, India, Laos, Myanmar, Thailand, and Vietnam, held on the occasion of the ASEAN Ministerial Meeting (AMM) in Bangkok July 28, 2000. MGC's goal is to strengthen the friendship and solidarity between the countries of the Mekong and Ganges (Mazumdar, 2009).

Since its establishment, India's trade with these countries in the Mekong sub-region has increased significantly, from \$1.36 billion in 2000 to \$27.59 billion in 2018, a 25-fold increase over two decades (De et al., 2020). To date, areas of cooperation have been expanded to include traditional medicine and modern medicine, agriculture and related industries, irrigation, micro-, small- and medium-sized enterprises, technology, skills development, and capacity building. Thailand, Vietnam, and Myanmar are the top three trading partners of India in MGC. In recent years, India's exports to Viet Nam has witnessed a phenomenal rise by over five times between 2008 and 2018. With an export of US$6.51 billion in 2018, Viet Nam has become India's largest export partner in MGC, followed by Thailand at about US$4.44 billion in 2018 (De et al., 2020). This trend indicated a high potential of value chains between India and ACMECS countries or in MGC. In August 2019, the 10th Mekong-Ganga Cooperation Foreign Affairs Ministerial Meeting (MGC) took place in Thailand. The ministers discussed the recent cooperation situation. They agreed to approve the Action Plan of the Conference from 2019 to 2022, to better meet development needs and respond to common challenges as well as further promote the potential for cooperation between the Mekong countries and India. This action plan added three new areas of cooperation, namely water resource management, science and technology, capacity building and skills development; continue to strengthen cooperation in agriculture, fisheries, health, commerce, culture, and tourism. The meeting also welcomed India becoming a development partner of the ACMECS. Also, at this meeting, the Deputy Prime Minister of Vietnam proposed some priorities for subsequent cooperation, including:

- strengthening cooperation and connection, developing a multimodal transport network connecting the Mekong region and India; especially the expansion of the East–West Economic Corridor, the southern economic corridor to India by land and sea, as well as expanding the India-Myanmar-Thailand expressway to Cambodia, Laos, and Vietnam,
- actively researching development assistance projects,
- developing trade and investment facilitation through the elimination of trade barriers, trade promotion, cooperation on customs clearance, quarantine, and regional supply chain development;
- promotig sustainable water management, in particular the implementation of projects on water resource data collection and monitoring, groundwater management, climate change adaptation and mitigation, flood control and drought (MEA, 2019).

Continental Southeast Asia, particularly the Mekong sub-region, has become the site of new commitments by external powers. The USA is at the forefront of this strategic competition, especially in the Indo-Pacific strategic framework. The LMI reboot has become a unique policy tool for the subregion. The USA's action has encouraged and enabled major external partners such as Japan and South Korea to strengthen and deepen relations with the Mekong countries through existing cooperation. They promote the integration of regional mechanisms in opposition to the LMC, which focuses more on engaging China with the Mekong countries (Williams, 2020). New commitments from external powers to benefit the Mekong countries should create more options for economic development. Regional countries need to grapple with excellent power dynamics and send a clear message that enhanced cooperation with external powers cannot be equated with taking sides on other issues.

9.4 The Role of Social Participation in Basin Governance

9.4.1 Defining and Conceptualising Social Participation

River basin governance is not only a technical issue, but also inherently a political and social one; because water inevitably flows across administrative boundaries and involves multifarious stakeholders who pursue diverse interests (Liu et al., 2020; Wang et al., 2017a, 2017b). As a result, river basin governance is a pluri-centric process that entails a series of accommodation, negotiation, conflicts, and cooperation, on which both state and non-state actors (e.g., non-governmental organisations, enterprises, and community members) have an impact.

The shifting nature of transboundary governance of an international river, such as the Lancang-Mekong, in particular, demonstrates increasing interconnectedness between state and non-state actors in the context of deepened globalisation and rapid development of modern information technologies (Dalby, 2010). This increasing interconnectedness substantially reshapes the structure of international river basin governance, the physical water that has traditionally been dominated and exploited by human beings, has been integrated with new features of power relations, social networks, cultural values, and individual subjectivities (Budds, 2009; Linton & Budds, 2014). The governance of international river basins is, therefore, not about governing water per se, but also about reshuffling a complex social-natural entity that is no longer exclusive to sovereign states or technical elites (Boström & Hallström, 2010).

As international river basin governance becomes an open platform to diverse non-state actors, the water sector has been experiencing a paradigm shift from state-led and technocratic management towards an increase of participatory based water governance, which has become particularly popular with international organisations, donors and NGOs (Sultana, 2015). For instance, in 1992, the Rio Declaration on Environment and Development stated that "Environmental issues are best handled with participation of all concerned citizens, at the relevant level" (United Nations, 1992). The EU Water Framework Directive is one of the most widely known examples which highly emphasises social participation in water governance (European Parliament & the Council, 2000).

Unlike the unanimous support of social participation globally, the defining characteristics and scope of social participation are relatively less clear among different actors. A World Bank publication defined participation as "a process through which stakeholders influence and share control over development initiatives and the decisions and resources which affect them" (Bhatnagar et al., 1996). Berry and Mollard (2009) characterised social participation in water governance by "the direct involvement of an array of people in decision-making and implementation of water policy or management", emphasising the opportunity that individuals and/or collectives have to "express their voices and articulate their arguments in public forums". In general, social participation refers to a process of involvement, but who should be involved, in what issues, to what degree, and how the involvement process should be organised?

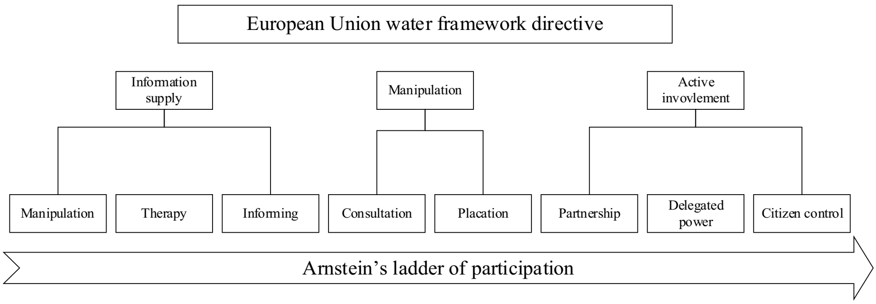

Fig. 9.1 Conceptual frameworks for understanding social participation. *Sources* Adapted from Arnstein (2019) and the European Parliament and the Council (2000)

Answers to these questions remain subject to debate. Therefore, some scholars have suggested that social participation should be understood as a principle rather than a rigorously defined subject (Webler et al., 2001).

Arnstein (2019)'s ladder of citizen participation and the EU Water Framework Directive are two widely cited conceptual frameworks for understanding social participation (Fig. 9.1).

9.4.2 Rationalities of Social Participation

Although social participation has gained popularity in the international community, its multifarious features have resulted in divergent understanding in terms of the scope, format, and degree of participation, thus raising challenges for consensus building and meaningful deliberation. Therefore, it is important to explore the reasons why social participation should be included in river basin governance. The clarification on rationalities of social participation could shed light into how to unify divergent expectations from different stakeholders and enhance river basin governance through effective social participation (Carr, 2015).

One of the most salient rationalities for social participation is that it is expected to improve the performance of river basin governance, which may be achieved through three major mechanisms underpinned by social participation. First, social participation is expected to provide space for deliberation and social learning, thus lead to high-quality decisions (Hedelin, 2007). As a "wicked" problem (Freeman, 2000), many believe river basin governance does not have a clear-cut solution prescribed for various complicated problems that emerge in the process of decision-making and policy implementation; rather, is an argumentative process, which brings together different stakeholders who can interact and communicate, is expected to gradually generate a common understanding, shared vision, and aligned knowledge, even the argumentative process starts from everyone's own interests and opinions (Ison et al., 2007; Pahl-Wostl & Hare, 2004; Reed et al., 2010). Second, social participation is expected to develop social networks and trust between participants (Lubell, 2007), which funnels existing values, beliefs, and rules towards river basin governance issues. As a result, social participation is expected to mobilise human and social capital to enable collaboration and coordination in redistributing responsibilities, sharing benefits, raising societal commitment, achieving common objectives, and facilitating policy implementation (Auer et al., 2020; Chai & Zeng, 2018; Putnam, 2000), all of which may provide creative, efficient and effective strategies for river basin governance. Third, social participation is expected to legitimise the decisions made through transparent and inclusive processes that allow participants to feel that they have influenced the decision based on a fair procedure (Carr et al., 2012). These perceived legitimate decisions are thus more likely to be accepted by the general public and easier to implement (Halvorsen, 2006).

Another rationality of social participation moves beyond the instrumental view that considers participation as a tool for performance enhancement. Instead, as Bourblanc (2010) put it, "participation is frequently perceived as an end in itself rather than as a means to an end" because participation has been increasingly connected with social-political struggles such as inequalities and asymmetric power (Berry & Mollard, 2009). In this sense, the rationale for social participation could lie in itself—for it signals deliberative democracy and an approach to empowering the vulnerable and minority groups. For instance, Clark (2013) proposes litigation as a form of social participation through an illustrative case of South Africa and argues that the right to water is an indigenous human right built upon participation. In Colombia's Pacific coastal region, participation has also evolved into water activism and social mobilisation, which are linked with broader struggles for development among black peasants (Perera, 2013).

9.4.3 Means of Social Participation

Empirical practices of social participation in the Lancang-Mekong River are much more diverse and complicated than its theoretical conceptualisation and rationalities. A variety of stakeholders, ranging from global network initiatives to local NGOs, from business enterprises to communities, have been actively engaging in the governance of the Lancang-Mekong River Basin. They have adopted different strategies (e.g., scientific research, capability building, policy advocacy, and citizen engagement) to exert influence on various issues such as climate change, biodiversity, hydropower development, and sustainable livelihood, revealing overlapping and interacting mechanisms of participation.

9.4.3.1 Global Network Initiatives

The International Union for Conservation of Nature (IUCN) and the Global Water Partnership (GWP) are two major global network initiatives that play a critical role in facilitating climate change adaptation and transboundary water cooperation in the Lancang-Mekong region.

IUCN is the world's largest membership union that brings together over 200 governmental agencies and 1,200 civil society organisations in a combined effort to conserve nature. Since 2016, IUCN have served as the secretariat for the Indo-Burma Ramsar Regional Initiative (IBRRI) to support the transboundary conservation and sustainable use of wetlands between Cambodia, Lao PDR, Thailand, Vietnam, and Myanmar (International Union for Conservation of Nature, 2019a). To support the implementation of the Ramsar Convention and the IBRRI, IUCN launched a specific project to build resilience of wetlands in the Lower Mekong region in 2017. This project aims to improve regional collaboration on transboundary wetlands management through capacity building and trainings activities including (1) ten climate change vulnerability assessments with local and national stakeholders at selected Ramsar sites in Cambodia, Lao PDR, Thailand, and Vietnam, which will be further developed into local adaptation plans; (2) a training programme developed to increase local wetland management capacity co-organised with Mekong Wetlands University Network; and (3) a citizen journalism programme initiated with the support of Thai PBS to raise the awareness of local communities about the impact of climate change on wetlands (International Union for Conservation of Nature, 2019b).

Another influential network is GWP. GWP was established by the Swedish International Development Agency, the United Nations Development Program and the World Bank in 1996 in response to international concern about deteriorating freshwater resources. The GWP's multi-stakeholder partnership mainly aims to support countries and communities in the sustainable management of water resources based on the principles of Integrated Water Resources Management (IWRM). To accelerate transboundary water cooperation among countries in the Lancang-Mekong River Basin, the GWP China and Southeast Asia Regions have set up a partnership with the Lancang-Mekong Water Resources Cooperation Center (LMWRCC) in 2017 (GWP, 2017a). The GWP has secured the LMWRCC's funding for capacity building activities and projects by supporting the Lancang-Mekong Cooperation mechanism through its neutral multi-stakeholder platform on which consultative meetings at the national, regional and inter-regional level can be organised (GWP, 2017b). For instance, the GWP has facilitated six member countries in identifying the national water development priority in the Five-Year Plan of Action on the Lancang-Mekong Cooperation (2018–2022) (Ministry of Foreign Affairs & International Cooperation, 2018). This strategic plan, drafted by the LMWRCC and reviewed by the national focal points through the network of GWP, was officially released in 2018.

9.4.3.2 International NGOs

The World Wildlife Fund (WWF) and The Nature Conservancy (TNC) are two influential international NGOs working in the Lancang-Mekong region to improve the capability of science-based water management techniques and biodiversity protection.

The main measures that the WWF uses to advance river basin governance are the production and dissemination of knowledge regarding responsible water use and infrastructure. For example, it has launched the Basin Report Card Initiative to help stakeholders create science-based report cards in their own basins using indicators of shared values (World Wide Fund for Nature, 2016). In 2014, the Luc Hoffmann Institute (LHI), established by the WWF and MAVA Foundation, kick-started the Linked Indicators for Vital Ecosystem Services (LIVES) project, which serves as a benchmark for identifying linked indicators for joint governance, planning, and management of the food-energy-water nexus. It is expected to formulate a knowledge basis of describing the complex relationships between the goals stakeholders have for their basins, and the levers that can be used to achieve those goals (Watkins et al., 2016). Moreover, WWF has led a series of stakeholder workshops and used the LIVES methods to discuss integrated planning and trade-offs in basin planning and management processes, which could amplify the impacts of the generated knowledge in community empowerment and civil society collaboration (Luc Hoffmann Institute, 2017).

TNC is a worldwide-reaching environmental nonprofit aiming to conserve the lands and waters. Dating back to the mid-1990s, TNC initially carried out a pioneer project on the Great River Basin National Park in northwestern China, and formally signed a memorandum of cooperation with the Yunnan Provincial Government to engage in biodiversity protection in the upstream of four Asian rivers, namely, the Jinsha-Yangtze River, the Lancang-Mekong River, the Nu-Salween River, and the Dulong-Ayeyarwady River (China Development Brief, 2017). In 2017, TNC also signed a five-year strategic cooperation agreement with the Lancang-Mekong Environmental Cooperation Center (LMECC). This agreement enabled the cooperation between TNC and the Chinese government on ecological and environmental protection, capacity building, policy dialogue, regional exchanges and cooperation in the Lancang-Mekong region. Similar to WWF, the work of TNC also focuses on knowledge generation and promotion, which allows TNC to give full play to its advantages and work with the LMECC to jointly promote scientific watershed planning and management, and to improve the capability of transboundary biodiversity protection.

9.4.3.3 Local NGOs

Local NGOs act actively as environmental stewards in the Lancang-Mekong region, mainly focusing on the issue of green infrastructure and sustainable overseas investment through the means of policy advocacy.

The past few years have seen local environmental NGOs continuously advocate against the development of hydropower infrastructure. For example, in 2011, local NGOs submitted a joint letter to the prime ministers of Laos and Thailand to advocate against the construction of the Xayaburi hydropower plant. In Thailand, Living River Siam mobilised communities along the river to raise awareness of its impact and organised community leaders to conduct an opening field investigation in the river basin (Herbertson, 2012). Two NGO coalitions, Vietnam Rivers Network and Rivers

Coalition in Cambodia, also adopted advocating strategies at the national and regional levels to lobby against the Xayaburi dam (Yasuda, 2015). In 2017, the Network of Thai People in Eight Mekong Provinces filed charges against related government agencies in Laos and Thailand on the grounds that the public had insufficient means to participate in the planning stage of the Pak Beng hydropower dam. The charges led to a second round of a technical consultation meeting in November 2018, which brought together government agencies, China Datang Overseas Investment Ltd., local NGOs, and experts to further discuss potential environmental and social impacts on upstream and downstream countries (The Mekong Butterfly, 2018). More extreme measures have been taken by some regional NGOs networks (e.g., Save the Mekong and International Rivers), which took a stronger opposition stand against the Pak Lay hydropower plant in August 2018 (Focus on the Global South, 2018).

In addition to advocacy, local NGOs also conduct research, foster dialogues on sustainable overseas investment, and engage in knowledge production. The Global Environmental Institute (GEI), a Chinese non-profit organisation, has brought talent and expertise to improve the policies and on-the-ground reality of overseas investment. GEI has been conducting a research project on China's Investment in the Greater Mekong Subregion-Laos, Vietnam, Cambodia, and Myanmar since 2013. It has published a series of reports to demonstrate the history, legal background, environmental and social risks faced by Chinese companies investing in these countries (Global Environmental Institute, 2016). Another Chinese environmental Think-Do organisation is Greenovation-Hub, which has also been working on green finance and investment and promoting cutting-edge environmental policy-making. In 2019, it coordinated and co-conducted the Handbook on Environmental Risk Management in China's Overseas Investment with an aim to provide better understanding of the destination countries' social and environmental regulations and cultures (Greenovation:HUB, 2019).

9.4.3.4 Business Enterprises

In addition to non-profit organisations, business enterprises also shoulder corporate social responsibilities and have taken a proactive part in river basin governance and hydropower development.

Coca-Cola launched a transformational partnership with the WWF in 2007 to conserve the world's freshwater resources in eleven key regions, including the Lancang-Mekong. Along the Chi River in Thailand, the partnership worked with farmers on agricultural improvements and reforestation activities that would support the freshwater ecosystem. In Vietnam's Tram Chim National Park, the partnership initiated a three-year project targeting the recovery of natural wetlands of the Plain of Reeds in 2008. With the project's support, the Tram Chim National Park has secured US$200,000 from the provincial government for infrastructure development, including building spillways to improve the water flow regime. In addition, the Coca-Cola and the WWF partnership were involved in legal proceedings by working with park officials and local governments, and eventually passed a new statute that allows for more appropriate management of a wetland ecosystem while helping local communities sustainably harvest park resources. During 2012, the partnership work spanned Cambodia, Laos, and Vietnam, focusing on advancing the conservation of the endangered Irrawaddy dolphin. They helped establish the Kratie Declaration on the Conservation of the Mekong River Irrawaddy Dolphin, an agreement that calls for increased monitoring and enforcement to reduce the use of improper fishing nets (World Wide Fund for Nature, 2012).

Huaneng Group Lancang River Hydropower Co., Ltd. (Huaneng) is China's second largest river basin hydropower company that is mainly engaged in the development and operation of hydropower in the Lancang-Mekong region. Over the years, it has paid careful attention to environmental impacts that hydropower stations would bring about and taken protective measures adapted to local conditions during the planning and construction processes. To preserve the ecological environment of the Baima Snow Mountain National Nature Reserve and the World Natural Heritage Site along the Three Parallel Rivers-the Yangtze River, the Yellow River, and the Lancang-Mekong River, Huaneng cancelled the Guonian hydropower station and lowered the normal storage level of the Wulonglong hydropower station. It further took effective actions to avoid soil erosion caused by engineering construction along the upper and lower reaches of the Lancang-Mekong River. In 2008, Huaneng originally established an animal rescue station within the Nuozhadu hydropower station to provide necessary care for the surrounding endangered wild animals. Rare plant and fish habitat protection areas have also been successively established to protect the indigenous wildlife resources in the tributaries (Wang, 2019). To promote the Lancang-Mekong Cooperation, the company continues to leverage its core advantages in hydropower, actively participating in the exchange and cooperation with downstream countries and enterprises to develop green hydropower in the Lancang-Mekong region.

9.4.3.5 Local Communities

Local community members are the key stakeholders engaging in projects on sustainable livelihoods organised by international or local NGOs. They are not only vital components of river basin governance in the Lancang-Mekong region, but also actors that could initiate participatory actions.

In the previously mentioned Tram Chim National Park project launched by Coca-Cola and WWF, local communities secured one of the Plain of Reeds' last strongholds in southern Vietnam. Nestled in the Mekong Delta close to the Cambodian border, Tram Chim is of great significance for local residents as the basis of their families' livelihoods. Therefore, the rapidly growing population has been turning it into one rice paddy after another, so that much of the historic wetland has disappeared. People have always fished in the park's pristine wetlands, even before some gained the legal right to do so. It was not until recently, however, that 200 households set up user groups to coordinate and cooperate on water governance affairs. The poorest and most vulnerable households have been part of this unique management approach that allows them to fish inside Tram Chim. In close collaboration with management staff, some fishermen have also become the park's ambassadors who contribute to preserving the park. They have learned the importance of the park's biodiversity and abandoned harmful fishing methods such as deadly chemicals and electrofishing. To date, there are over 50,000 people who live closest to Tram Chim working with rangers to protect wetlands (World Wide Fund for Nature, 2015).

Villagers, living in the upstream areas of the Three Parallel Rivers located in China, are also developing sustainable livelihoods with technical and financial support from domestic NGOs such as GEI and Shan Shui Conservation Center. Ecological compensation programmes have been set up and local villagers could receive cash payments by providing ecological services such as participating in water quality monitoring and species observation. In 2016, more than 2,000 herdsmen received training and conducted monitoring activities in six tributaries of the Three Parallel Rivers. To achieve a win–win situation of ecological protection and community development, several communities have established economic cooperatives to improve sustainable livelihoods working on ecological farming and herding, traditional handicrafts, Tibetan tea production, and eco-tourism (Wang, 2016).

9.4.4 Outcomes of Social Participation

9.4.4.1 Positive Outcomes

Although mixed with challenges and complexities, social participatory engagement in the governance of the Lancang-Mekong have generated some promising outcomes.

First, information and data collected and disseminated by NGOs and civil society groups have facilitated informed and transparent decision-making on investment projects. For example, before the construction of the Xayaburi dam, the Laos government strictly conducted the Environmental Impact Assessment (EIA), the Social Impact Assessment (SIA), the Environmental Management Plan (EMP), and the Resettlement Action Plan (RAP) as a response to active appeals of local NGOs. The construction of Pak Beng hydropower plant has also gone through the second round of technical consultations with affected people and all stakeholders. Furthermore, multi-stakeholder platforms with both public and private sectors involved have facilitated transboundary water collaboration among the riverine countries. For example, the collaboration between the LMWCCC and GWP since 2017 has allowed non-government stakeholders to be an integrated part of the Lancang-Mekong Cooperation.

Second, some business enterprises have complied with their corporate social responsibilities and leveraged capital-rich investment in sustainable economic, social, and ecological development. For example, the global freshwater conservation campaign launched by Coca-Cola and WWF in 2007 has leveraged a total funding of $20 million in eleven regions. In particular, the Tram Chim National Park project based in the Mekong River Basin has secured an annual expenditure of $250,000 for the recovery of natural wetlands of the Plain of Reeds in southern

Vietnam (World Wide Fund for Nature, 2012). Hydropower private investors, such as Xayaburi Power Co., Ltd. and Huaneng, have committed to developing green hydropower using the best available technologies to prevent and minimise all environmental and social risks, including fishery resource conservation, sediment routing, navigation, and riverbank erosion.

Last but not least, local people have been increasingly aware of social-ecological issues through participatory approaches structured on community mobilisation and village engagement. For example, through the Basin Report Card initiated by WWF, a professional class of facilitators within international NGOs have become brokers to stimulate local interests in water governance. The villager-led Thai Baan Research, an emancipatory means of knowledge production developed in the late 1990s and expanded to other areas, has also empowered the grassroots to voice their concerns on long-term potential threats that development plans will bring about. This approach has not only included indigenous groups such as the Chiang Khong Conservation Group and regional NGOs such as the South East Asia Rivers Network, but also gained the support of government officials and other organisations such as IUCN and Oxfam. It has rapidly gained credibility and become complementary to decentralisation initiatives, bringing in local farmers' and fishers' knowledge that has been vividly communicated to others through photos, videos, and booklets (Lebel et al., 2007; Sretthachau, 2007).

9.4.4.2 Negative Outcomes

Despite the positive achievements, social participation in the Lancang-Mekong River, in some respects, have demonstrated signals that it can be transformed into political instruments for external interventions in state and regional governance, casting shadows over future collaborative governance. These external interventions are not ideologically neutral, nor are they fully motivated by the interests of local stakeholders; rather, they are intrinsically political and filled with geopolitical contestations. Historically, the Lancang-Mekong region has been rife with diverse geographical imaginaries, which include not only the Cold War "front line" that divided communism and capitalism, but also the "corridor of commence" that signified the prevalence of neoliberalism promoted by international donors and funders (Bakker, 1999). More recently, the growing influence of China has received many critics from the West, which depicts China as the "upstream dragon" (Magee, 2011) and "water power" (Lee, 2014) which holds great economic, political, and hydrological strengths to "control" downstream countries (Biba, 2012; Yeophantong, 2014). These geopolitical contestations, reflected in social participation of river basin governance, generate two main negative outcomes.

One prominent outcome is prevalent social conflicts associated with development projects at the sub-national level (Dugan et al., 2010; Galipeau et al., 2013). As mentioned earlier, the rationale for social participation is to create space for deliberation, build trust, legitimise decisions, and thus improve the performance of water governance. In this sense, it is important to bear in mind that the objective of social participation is to facilitate cooperation rather than to create social conflicts. For instance, NGOs are not affiliated to government agencies; their objectives are not necessarily in contradiction with the government either. Although civil society groups and international organisations have contributed significantly in mitigating environmental and social impacts of development projects (e.g., hydropower dams) on vulnerable groups, one should also remember that the failure of development is by no means conducive to local livelihoods either. In practice, the essence of social participation can be lost, sometimes even manipulated, as development projects proposed by national governments are translated into "battle fields" where different stakeholders pursue their own interests in the process of participation. For instance, Thai NGO collectives, such as Save the Mekong and People's Network of Isaan Mekong Basin, chose to boycott the prior consultation phase for dam projects which was an official communication platform built by the MRC (Jirenuwat & Roney, 2020); and further, they refused to reach a consensus through constructive conversations and discussions with government agencies. Likewise, the USA-backed institutions, Eyes on Earth and Stimson Center, deliberately used flawed data and models to hype up the 2019 lower Mekong drought, exacerbating transboundary tensions between the MRC member states and China (Kallio & Fallon, 2020). The behavior of such NGOs in using flawed data and hyping up implied their objective is making conflicts rather than promoting cooperation. Against this backdrop, it is worth noting that many non-state actors are value-driven entities with specific goals, which similar to those of the states or private companies, may also include seeking independence, influence, and profits (Chen et al., 2013; Knutsen, 2013). As a result, the boundary between non-state and state actors is more blurred than many would expect. The lack of social participation could be manufactured as an excuse by some participants, which creates barriers instead of facilitating cooperation in river governance.

The other negative outcome is discursive polarisation. The confrontational approaches taken in the process of participation are not only a manifestation of power struggles, but also breed opposite framings of the Lancang-Mekong among different stakeholders. For instance, a polarising discourse is situated between hydropower development and ecological conservation. The development discourse overwhelmingly emphasises the importance of energy generation, irrigation, and flood control for local livelihoods (Ho, 2014; Middleton & Allouche, 2016) and argues that hydroelectricity is the most appropriate option for development in the lower Mekong countries where alternative energy sources are not available (Zhang, 2017). On the other hand, the conservation discourse chooses to see the other side of hydropower—displacement of local residents, habitat loss, and socioeconomic inequalities (Biba, 2012, 2014; Magee, 2011; Yeophantong, 2014). As a result, the polarising discourse could deepen societal division rather than build consensus, rendering a contested public space where collaboration becomes impossible. Another polarising discourse concerns the relationship between China and the downstream countries. Since the Lancang-Mekong has been filled with strategic competition between superpowers, social participation is often entangled with shifting geopolitical contestations (Hirsch, 2016). As Chinese investments continuously grew after the 1997 financial crisis (Middleton et al., 2012), the discourse used in environmental advocacy by civil society groups seems to have placed China at the opposite side of the environment, despite Western dominated donors and banks (e.g., World Bank) having long championed hydropower development in the Mekong (Yong & Grundy-Warr, 2012). As a result, polarised discourse in social participation could become a part of a bigger political agenda that attempts to contain Chinese influence in the Mekong rather than to explore an acceptable path toward sustainable development. This is an often-neglected fact at the transnational level where power asymmetries easily shadow the truths and realities—it is easier to simply label the powerful as the "evil developers" and the weak as the "innocent protectors" than to dig into socioeconomic complexities and explore hidden sources of conflicts.

9.4.5 Overcoming the Challenges and Complexities of Social Participation

As participatory approaches to governing river basins are experimented with and tested around the world, we have increasingly seen practices of social participation in the Lancang-Mekong River Basin. However, the goal of participatory water governance, which is to create arenas for discussion, dialogues, capacity building, and empowerment, is far from being achieved (Berry & Mollard, 2009, p. 315). Social participatory engagement in the Lancang-Mekong region also faces challenges and complexities, concerning the issues of legitimacy, information and knowledge, inclusiveness, and capability.

First, as the defining features and degree of social participation vary across different institutional frameworks at both regional and national levels, the legitimacy of participatory decision making, accordingly, is subject to debate and elucidation. In other words, government agencies, experts, international organisations, local NGOs, and community members may all have a different understanding of "representativeness" and "fairness" in the decision-making process, making participation itself a contested notion. Yet regardless of the way participation is organised, a critical component for legitimacy is that the decision-making process is clearly structured and displayed in an institutionalised way (Chilvers, 2009; Rowe & Frewer, 2000), which remains elusive in the Lancang-Mekong River Basin. The Five-Year Plan of Action on Lancang-Mekong Cooperation (2018–2022) has established a leader-led, government-guided working structure to maintain high-level dialogues and exchanges. However, institutionalised social participation remains inadequate. At the national level, the scope of institutionalised social participation, such as EIA is still relatively narrow and encounters practical difficulties when sensitive issues (e.g., large-scale hydropower projects) are involved (Bian, 2017).

Second, the general public still has limited access to sufficient information and limited input into knowledge production in the Basin governance. On the one hand, the inadequacy of institutionalised participation opportunities in major government decisions, to a large extent, prevents the general public from being fully informed in a timely, true, and comprehensive manner. For a legitimate decision to be made, greater disclosure of key information is essential, particularly before a hydraulic project moves to the next stage (Middleton, 2018). On the other hand, gaps between expert knowledge and lay knowledge remain salient and lay knowledge has rarely been acknowledged despite the limitation of technical and managerial expertise (Lopez Cerezo & Gonzalez Garcia, 1996). Scientific and technical expertise are usually deployed to justify policy and development plans, whilst limited opportunity is offered for inhabitants who have a living understanding of the water environment (Käkönen & Hirsch, 2009). Although there have been villager-oriented attempts, in several countries, to conduct studies on rivers and formulate endogenous findings, it seems particularly difficult for local people to convince the governments and get their input comfortably accepted in the decision-making process (Herbertson, 2012). In order to address sustainability challenges, knowledge generation needs to move rapidly from a disciplinary linear 'tree' model to an interdisciplinary 'web' model by involving different stakeholders. Liu et al. explains how such a shift is useful by looking at case studies in the context of water management.

Lastly, building consensus and increasing inclusiveness of social participation remains a predicament. On the one hand, complex conflicts of interest exist among actors involving the states, government agencies, private investors, and water user groups, such as farmers and fishers in the Lancang-Mekong Region. These actors compete on spatial scales of administration, hydrology, ecosystems, and economy, and also on different territories at local, provincial, national, or regional levels (Dore & Lebel, 2010), which inevitably create challenges to consensus building, in spite of dialogues and other forms of deliberation engagement. On the other hand, there exists technical, financial, and social gaps among civil society groups, which prevents inclusive public deliberation from being an institutional protection for the disadvantaged. The empirical evidence has indicated that international NGOs, such as WWF and TNC, play much bigger roles in the Lancang-Mekong region than small grassroots NGOs (Fabres, 2011). With sufficient human capital and funding, international organisations are able to dominate the discourse and practices, whereas the impacts and autonomy of indigenous groups are largely confined (Fabres, 2011). Likewise, few Chinese NGOs are able to participate owing to limited capacity. Only a few sporadic actions have been taken in the upstream Chinese territories. This intra-society gap also occurs among different social groups. Low-income ethnic women have experienced exclusion from community water decision-making (Nguyen et al., 2019) and project-led community participation is mainly dominated by local elites. Whereas those whose livelihoods and everyday practices are greatly impacted are mostly marginalised in the participatory process.

In light of these challenges that may prevent social participation from fully realising its expectations, some strategies should be explored to address the challenges and improve future collaborative engagement in the Lancang-Mekong River Basin governance.

First, a paradigm shift from elite-led participation to inclusive participation is needed. Particularly, marginalised and less represented groups should be empowered and play a bigger role in knowledge production. For one thing, current practices indicate that the scope and actors that are effectively involved in social participation are not only limited, but also easily politicised. To this end, it is of vital importance to empower excluded social groups and grassroots actors, rather than international organisations or transnational enterprises, to facilitate inclusive representativeness and to create a space of fair exchange. For another, knowledge is critically shaped by cognitive, cultural, political, and institutional factors, and thus knowledge that better fits Western knowledge systems normally receives more recognition than indigenous knowledge (Briggs & Sharp, 2004; Lemos, 2015). Therefore, the co-production of knowledge is important because it incorporates multiple forms of knowledge and ensures broad representation instead of elite domination. Situational knowledge of riverside communities and various civil society research initiatives, such as Thai Baan research in Thailand and Sala Phoum in Cambodia should be acknowledged in the participatory decision-making process (Middleton, 2018).

Second, it is important to establish institutionalised social participation through regulations, policies, and laws (Berry & Mollard, 2009, p. 316). Formal deliberation procedure is a salient example that could enable power to be distributed more fairly, thus being conducive to overcoming power imbalances in practice. Simply putting people with different priorities together is not enough to foster social participation, but an institutionalised deliberative engagement makes participation meaningful; because it allows active and reflexive management of the negotiation among diverse participants who have a variety of opinions, positions, interests, and values. A formal deliberative procedure allows multiple stakeholders, including minorities, women, migrants, and diverse groups of the poor, to engage in conversations and dialogues where everyone is given a relatively fair opportunity to articulate their reasoning and claims (Dore & Lebel, 2010). In this sense, the deliberation procedure itself has served the purpose of participation and enabled decisions to be viewed as legitimate by participants, regardless of the outcomes (e.g., consensus is reached or not) of the deliberation.

Third, the use of modern technologies may play a bigger role in empowering the general public. In China, the rapid development of internet infrastructure (e.g., advanced sensors, smart data processing and sharing, web-based geographical information system, and cloud calculation) and the increasing ability of the general public to use smartphones and apps have allowed them to supervise the performance of water governance easily (Jia & Li, forthcoming), thus opening the channel for social participation. For example, water agencies in several provinces have developed a variety of "river chief" smartphone applications, which allow the general public to upload photos and report water-related problems they see and experience in everyday life (Huang & Xu, 2019).

Last but not least, state-led participation should act more proactively. For instance, China has established an expert argumentation system, which mandates that any newly built, reconstructed, and expanded hydraulic project must be reviewed, debated, and approved by a panel of experts before construction (Jia & Li, 2021). This institutionalised procedure actively brings in expert opinions, which could reduce potential conflicts and legitimise decisions on hydraulic infrastructure. Likewise, information disclosure is central for social participation, both in terms of the quantity and quality of information. Rather than react passively, government agencies could voluntarily share hydraulic data and make the information not only accessible to the scientific experts but also to the general public. The Lancang-Mekong Water Resources Cooperation Information Sharing Platform launched by the Chinese government in 2020 has started to play a critical role in data sharing with other riparian partner countries. Proactive information sharing not only improves transparency, but more importantly, increases the legitimacy of decisions, which greatly facilitates cooperation in river basin governance.

9.5 Outlook for Future Development of Basin Governance Cooperation

Basin-based integrated water governance continues to develop and strengthen as showed by the phenomena that China's top leader Xi Jinping personally advocated and promoted the great protection plan of the Yangtze River, the ecological protection and high-quality development plan of the Yellow River Basin.

Integrated River Basin Governance in the Lancang-Mekong River Basin will certainly broaden and deepen along with the strengthening desire of people of riparian countries for better water management, more powerful will for basin community cooperation, and capacity building including more advanced knowledge and technology. Closer basin cooperation is a consensus among riparian countries. The LMC mechanism has been deepening. On June 8, 2021, the sixth LMC foreign ministers' meeting was held in Chongqing, China, issued a joint statement on strengthening Lancang Mekong countries' sustainable development cooperation, and put forward proposals on deepening local cooperation between Lancang Mekong countries.

Cooperation between different mechanisms is also being strengthened, especially the cooperation between the two main basin cooperation mechanisms—LMC mechanism and MRC—is deepening. The new CEO of the MRC Secretariat, Dr. Anoulak Kittikhoun, stated that beyond a desire to deepen regional and international partnership, a crucial priority is to expand efforts to monitor and measure how economic development, water-infrastructure projects and climate change—including more floods and drought—affect the many millions who dwell in the Lower Mekong River Basin (MRC, 2022).

One of the main directions of all programmes and formats of cooperation is cooperation in the field of science, education and technology. International scientific research and educational centres and institutes have been created and continue to be created. Subsequently, this will only lead to an improvement in the quality of all actions and decisions taken.

There may be also some interferent to the cooperation. One interruption factor is big power competition between USA and China. While China put forward "One Belt One Road Initiative", USA put forward "Free and Open Indo-Pacific Strategy".

Recently, President Biden further put forward “Indo-Pacific Economic Framework” to construct a regional economic partner organization but plan to exclude China. This operation may make troubles for the basin countries to cooperate with China. At the same time, disputes between riparian countries, such as the sovereignty dispute between China and Vietnam over islands in the South China Sea, may also interrupt the basin cooperation.

The basin countries must sustain economic growth and work together to follow the Agenda for achieving the 2030 Sustainable Development Goals. After all, any mutually beneficial cooperation has a high chance of achieving the main goal—the well-being of the population in all countries of the region.

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