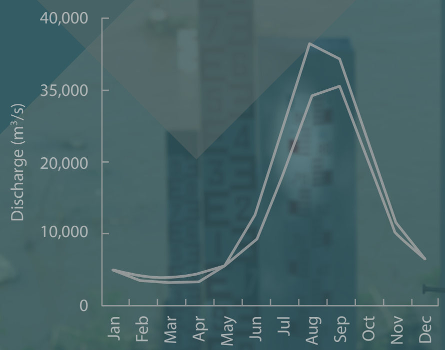

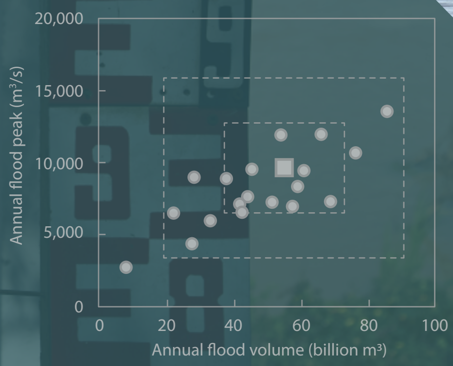

Technical Report - Phase 1

HISTORICAL CHANGES OF FEATURED HYDROLOGICAL CONDITIONS AND THEIR CAUSES

The Joint Study on the Changing Patterns of Hydrological Conditions of the Lancang-Mekong River Basin and Adaptation Strategies

September 2023

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Historical changes of featured hydrological conditions and their causes

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Lancang-Mekong Water Resources Cooperation Center

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Lancang-Mekong Water Resources Cooperation Center
Suite D, No.3 South Yuyuantan Road, Haidian District, Beijing 100038, China
Telephone: +86-10-68781079 | E-mail: program@lmwater.org.cn |www.lmcwater.org.cn
Mekong River Commission
184 Fa Ngoum Road, Unit 18, Ban Sithane Neua, Sikhottabong District, Vientiane 01000, Lao PDR
Telephone: +856-21 263 263 | E-mail: mrcs@mrcmekong.org | www.mrcmekong.org

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ABBREVIATIONS AND ACRONYMS

CRU TS	Climate Research Unit gridded Time Series
DEM	Digital Elevation Model
GIS	Geographical Information System
LMC Water Center	Lancang-Mekong Water Resources Cooperation Center
LMC	Lancang-Mekong Cooperation
LMRB	Lancang-Mekong River Basin
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SRI	Standardised Runoff Index
SWAT	Soil & Water Assessment Tool
THREW	Tsinghua Hydrological Model based on Representative Elementary Watersheds

EXECUTIVE SUMMARY

Background

The LMC Water Center and MRCS are working on furthering cooperation between all the Lancang-Mekong River Basin (LMRB) States. Initially, this is being done through advancing joint activities and building on past collaborative research studies. This has already been fruitful. In both 2016 and 2019, joint studies conveyed objective information about the severe droughts to the public and made scientific evaluations of the effects of water supplement from the Lancang reach to alleviate the drought conditions on the Mekong reach of the mainstream.

Following the signing of a Memorandum of Understanding (MOU) between the LMC Water Center and MRCS in December 2019, the parties proposed a "*Joint Study on the Changing Pattern of Hydrological Conditions of the Lancang-Mekong River Basin (LMRB) and Adaptation Strategies*." This initiative aims to provide a better understanding of hydrological changes in the LMRB as a result of climate change, land use/cover change, and other water use activities. This will form the basis for proposals for operational and infrastructural measures to build climate resilience in the Basin.

The Joint Study comprises three components:

- **Component 1**: An assessment of the historical changes in the hydrological conditions and the underlying causes of these changes.
- **Component 2**: Predict future trends in hydrological conditions due to climate change and proposed water resource developments.
- **Component 3**: Propose strategies for the riparian States to adapt to climate and demographic changes, thereby supporting continued sustainable management and development of the LMRB.

The study is further separated into two Phases:

- **Phase 1 (2022)** is reported here. It focuses on changes in the hydrological conditions and the causes of these changes as envisaged under Component 1. It also makes preliminary recommendations for adaptation strategies and outlines issues to address in Phase 2.
- **Phase 2 (2023–2024)** will start in January 2023. This Phase will take up the recommendations from Phase 1 before addressing components 2 and 3.

Selecting the periods to assess changing mainstream flows

The streamflow of the LMR has exhibited significant changes from 1980 to 2020, with the year 2009 identified as the changing-point year. Over the last 20 years, there have been at least three extreme droughts, in 2004–2005, 2016, and 2019–2020. Of these, the more recent events have coincided with the record low flows and an increasing debate on the relative contributions of low rainfall to the low flows and increasing storage in the LMRB.

It was therefore decided to separate the last 20 years, for which a good dataset is available, into the 2000 to 2009 and 2010 to 2020 periods. Some 20% of the total storage in the whole basin, including mainstream and important tributaries, was developed in the 2000 to 2009 period, and the remaining 80% of the approximately 100 billion m^3 of active storage was gradually developed from 2010 to 2020. At present, the total storage in the LMRB amounts to some 27% of the mean annual runoff (MAR) at

Stung Treng of 366 billion m^3. Drought-prone basins (like the Murray-Darling River and Colorado River) typically have storage for over 200% of the MAR.

Despite the utility of separating 2000 to 2009 and 2010 to 2020 periods, it is important to recognise that storage was gradually added over the last 10 years. During this time, consumptive water demands for irrigation also increased rapidly, and some of the more severe meteorological consequences of climate change were observed and monitored. To discover the causes of hydrological regime changes, the severe meteorological droughts of the last decade as well as the increased storage and water use should be considered. This report has taken the first steps toward this.

Methodology

The assessment outlined in this report was based on an analysis of the observed climate and flow data made available by both the LMC Water Center and MRC, as well as from international sources. This was supplemented by modelling the rainfall-runoff and water system characteristics of the basin. The latter used the SWAT and Source modelling platform, which were also used for some recent MRC studies, including the MRC Council Study, as well as the THREW model, which has been applied in the studies of many watersheds around the world by the Tsinghua University. This suite of models provided the basis for scenario analyses, which could assess whether the changes observed are due to the storage or changes in the climate.

Droughts were analysed using the Standardised Precipitation Index (SPI), the Standardised Precipitation Evapotranspiration Index (SPEI), and the Standardised Runoff Index (SRI) made available from the CRU TS, ERA5-Land, and CHIRPS.

Results and analysis

Changes in the spatio-temporal distribution of streamflow

The streamflow of the LMR has exhibited significant changes from 1980 to 2020, with the year 2009 identified as the changing-point year. Notably, no significant hydrological changes were observed between 1980 and 2009. However, from 2010 to 2020, the annual flow of the LMR was found to be lower than that of 2000-2009, which can be attributed to drier climate conditions. Despite this, the seasonal pattern of LMR flows remains pronounced, with the dry season flows being amplified and the wet season flows reduced due to basin development. Moreover, when compared to 2000-2009, the daily, weekly minimum and monthly minimum flows for 2010-2020 at all mainstream stations show an increase, while the maximum flows exhibit a decrease.

The trend observed in the data indicates a shift in the timing of minimum daily flows over the past two decades. From 2000 to 2009, the minimum daily flow typically occurred in early April. However, from 2010 to 2020, the minimum daily flow shifted to mid-March. This change suggests a potential trend towards earlier minimum daily flows in recent years about three weeks. Furthermore, the average timing of maximum daily flows of the mainstream stations remains relatively the same (late August or early September).

The data shows a significant shift in the seasonal volume ratio at upstream stations, specifically at Jinghong and Chiang Saen, from 20% dry season volume over 80% wet season volume for the period 2000-2009 to 40% dry season volume over 60% wet season volume for the period 2010-2020. This suggests a substantial increase in the dry season volume and a decrease in the wet season volume at these stations.

On the other hand, downstream stations, such as Chiang Khan to Nong Khai/Vientiane, showed a smaller change in the seasonal volume ratio. It shifted from 20% dry season volume over 80% wet season volume for the period 2000-2009 to 30% dry season volume over 70% wet season volume for the period 2010-2020. Similarly, Nakhon Phanom/Thakhek to Stung Treng showed a shift from 15% dry season volume over 85% wet season volume for the period 2000-2009 to 20% dry season volume over 80% wet season volume for the period 2010-2020.

As the whole basin features lower precipitation in the latter period, furthermore, there was a decrease in the annual flow at Jinghong, amounting to -9 billion m^3 or a reduction of 17%. Similarly, the annual flow at Luang Prabang, Nong Khai/Vientiane, and Stung Treng experienced reductions of -2 billion m^3 (-2%), -17 billion m^3 (-12%), and -78 billion m^3 (-18%), respectively.

The analysis of flood patterns reveals that 2019 and 2020 were extreme hydrological drought years in the Lancang/Mekong mainstream, exceeding the two standard deviations. Additionally, several years in 2010-2020, particularly downstream, experienced significant hydrological droughts beyond one standard deviation. In contrast, the years from 2000-2009 saw deviations from the one standard due to higher flood volumes or severe flood years.

Changes in flood pulse of the Tonle Sap Lake

Overall, the accumulated volume and duration of the reverse flows during 2010–2020 have considerably reduced when compared to 2000–2009. This is associated with both reduced wet season rainfall (which reduced the flows in the lower Mekong mainstream) and increased storage and water withdrawal in the whole basin. Thus, the combined impacts have reduced the flows from the lake to the Delta at the onset of the dry season.

During 2010–2020, the total volume and duration of the reverse flows to the Tonle Sap Lake have considerably decreased. This points toward recent meteorological drought conditions of 2016 and 2019–2020 as one of the main causes of the changes. A more detailed examination of the factors influencing alterations in the flow of the Tonle Sap Lake will be undertaken in the subsequent phase of the study.

What contributes to changes of hydrological conditions in the basins?

Two key factors contribute to hydrological changes in the LMRB: natural factors, including precipitation patterns, evaporation rates, soil properties, topography, and human activities such as infrastructure development, water management and land cover and land use changes. These two factors interact and influence the amount, timing, and water distribution within the Basin.

For this study, the natural factors considered are the meteorological/hydrological drought using the SPI, SPEI, and SRI:

- **Long-term trend**: Generally, the dry and wet seasons show trends toward more severe droughts over large areas of the LMRB. Furthermore, the period of 1950–2021 shows considerable spatial changes in both these indexes when compared to 120-year data (1901–2021). This suggests that the trend towards ‘drier’ conditions is more recent and is likely to be related to the changing climate.

- **Frequency:** The trend is for significant increases in drought frequency over large areas of the LMRB during the last 20 years. This was particularly evident in the exceptional drought category for the lower Lancang and upper Mekong regions. A great degree of consistency of the drought frequency distribution of SPIs estimated from various meteorological datasets (CRU TS, ERA5-Land, and CHIRPS) reveals that the LMRB has been exposed to more frequent meteorological droughts in 2010–2020.
- **Duration:** Trends in droughts duration are for longer droughts over large areas of the basin. Severe and exceptional droughts were also prolonged in many parts of the basin, and the exceptional drought was significantly prolonged in the middle part of the whole basin.
- **Intensity:** The overall trend in drought intensity is for the mild droughts to become less severe, whereas there is a slight intensifying in the severity of the exceptional droughts over most of the basin and significant change for small patches in the lower Lancang section.
- **Role of the El Niño phenomenon:** There is considerable evidence that meteorological droughts in the LMRB are driven by the presence of an El Niño event and that the intensity of the event is a good indicator of the intensity of the meteorological drought over the Basin. Forecasts of the El Niño events will therefore be a good indicator of the potential drought.

From the above analysis of long terms trends, frequency, duration, intensity and role of the El Niño, it is concluded that climate change shows a significant impact in the basin.

Frequency changes in meteorological droughts (SPI by CHIRPS) and areal hydrological conditions (SRI by VIC model) drought frequency changes between 2000–2009 and 2010–2020, have revealed a **remarkable similarity in drought frequency changes of the meteorological and hydrological droughts** over the Mekong River Basin. The frequency of both meteorological and hydrological droughts increased intensively during 2010–2020 compared to 2000–2009. Moderate and severe droughts have the most significant frequency spatially. The results also indicate that meteorological factors play a dominant role in hydrological processes and changes.

What caused the differences in the 2000–2009 and 2010–2020 flows?

The separation between the periods 2000–2009 and 2010–2020 is based on the available dataset. It was observed that the annual flow of the LMR during the 2010–2020 period was lower compared to the 2000–2009 period, likely due to drier climate conditions. Additionally, the impact of basin development is evident in the seasonal flow patterns, with amplified dry season flows and reduced wet season flows in the latter period.

Irrigation is the most prominent consumptive water use in the Mekong River Basin, and the area under irrigation has also gradually expanded over the last 20 years. Total water withdrawal in the basin was estimated at 62 billion m^3, or 13% of the river's average annual discharge, and irrigation withdrawal accounts for 56 billion m^3 or 91% of the total in 2012. Total water withdrawal in the Lancang River basin is 2.8 billion m^3 in 2020, a small portion of the total water withdrawal of the whole basin. Though consuming large amounts of water, due to gradual changes, irrigation is not expected to contribute substantially to the hydrological changes between the two periods. There may be some reduction of flows due to irrigation in the dry season, and recent increases in irrigation (together with sand mining) in the basin may have played some role in increasing the potential for saline intrusion. Similarly, while there have been remarkable increases in the diversion of flow for domestic and industrial uses, this is comparatively smaller fraction of the flows on the mainstream. But it is noticeable that rapid growing population and economy in the Mekong delta may generate unprecedent demand of water from the

Mekong. It is needed to share more information and data of tidal changes, water and land use, and ground water level in the past 60 years or even longer for scientific research.

Although increased hydropower storage capacity in the whole basin does not consume much water, it does contribute to the changes of hydrological conditions, in particular extreme flow in the wet and dry seasons.

The simulated results from the THREW and SWAT/Source models provide consistent trends of the hydrological impacts of the water resource development and climate. The two model packages demonstrate that the development of water storage has increased the low water levels in the dry season and decreased the high flow in the wet season in the whole basin. This is more evident at upstream stations but less evident further downstream, where the contributions from the portions of the tributaries are greater.

Opportunities for adaptive management

While all six riparian states' foreign policies are founded on respect for sovereignty, the key challenges for the Lancang-Mekong River are transboundary and requires joint actions to support the reasonable and equitable use of the shared water and avoidance of significant transboundary harm. This is evidenced by occasions where supplementary releases have been made to mitigate the impacts of the droughts and extreme low flows in the Mekong mainstream reach, thanks to the political commitment of the six basin countries to enhancing joint efforts to address basin-wide flood and drought with the commencing of the LMC/MLC mechanism, together with the MRC cooperation. Similarly, the MOU signed between the LMC Water Center and MRC and this present Joint Study also underpin the growing recognition that increased cooperation is needed.

In general, increasing storage can provide opportunities for regional climate adaptation. Supplementary releases from storage can be used to mitigate the impacts of severe droughts (i.e., 2016), and if well coordinated among the riparian countries in operation and management of the storage, can mitigate the impact of storage on the flood, sediment trapping and fisheries. This may also provide the opportunity to adjust the timing and volume of the return flows to the Tonle Sap Lake.

Supplementary releases, however, pose short-and medium-term risks and additional costs to generation capacity. These will need to be quantified and accepted by all parties. This means including electricity generation capacity in a basin-wide operational model. It will also require short-term (up to 2 weeks) and medium-term (seasonal) forecasts to be included in the models. The risks across the WEF nexus can then be analysed on a rolling basis as the wet season unfolds, enabling a frequent revisit of the potential for supplementary releases. It should be pointed out that supplementary releases may need to be institutionalised only through consultation and negotiation in order to make it workable in the long run if such releases are considered necessary by all parties involved. There are a few cases in other parts of the world that could shed some light on such arrangements.

In the longer term, smaller generation facilities or energy conservation measures can be considered to fill in the 'energy generation gaps' due to supplementary releases. These options may include pumped storage or floating solar options. Additional storage operated primarily for flow compensation can also be considered. Non-infrastructural interventions should also be considered as medium to longer-term strategies, like energy demand management, water conservation in all sectors, natural-based solutions (e.g. preservation of existing natural storage on wetlands and floodplains) and shifting the regional economies towards more climate-resilient livelihoods.

Recommendations

While Phase 1 of the Joint Study has made important advances in our joint understanding of the changing patterns on mainstream flows, there are still some issues that must be addressed. Recommendations for further work are:

Short-term

- **Enhanced data and information sharing**. As global climate change and the associated droughts and floods will play an increasingly important role in driving the basin's hydrological conditions, it is critical for basin countries to share more information on meteorological flow conditions. This should be expanded to include the tributaries. Near real-time sharing of storage levels and hydropower operations will also be critical to support operational models and adaptive management of the basin. More information and data on tidal changes, water and land use, and groundwater level in the past 40 years or even longer in the Mekong delta is also critical for scientific research with a basin-wide perspective. The information sharing platform proposed under the LMC cooperation framework provides an unprecedented opportunity to support this process. It is encouraged to explore and improve the better and more effective notification of storage releases and restrictions, and both LMC and MRC are ideal mechanisms to enhance notification of unusual releases and restrictions.

Medium-term

- **Coordinated management of water resources**. It is recommended that riparian countries jointly formulate action plans and strategies for coordinated water resource management. The LMC water cooperation's Five-year Action Plan (2023–2027), which is currently being formulated, and the MRC's Basin Development Strategy (2021–2030) and the associated adaptive management plan provide the opportunity to advance this.
- **Comprehensive drought and flood management strategy**. Climate change driven floods and droughts will play an increasingly significant impact on regional development. Both structural and non-structural measures will be needed to mitigate these impacts. It is recommended that a comprehensive Flood and Drought Risk Management Strategy is formulated based on the prevention, protection, and preparedness (3-P) principles.
- **More Joint Studies**. Phase 1 of this current joint study lays a solid foundation and highlights the benefits of combining the skills and experience from all the riparian countries. It has highlighted that joint studies can support the realisation of the 2030 SDGs. However, there are many issues that remain unclear. It is critical that coordinated water resources management and the flood and drought strategies proposed above are based on a common understanding of the challenges and sound science, including sediment movement/transport, salinity intrusion, ecological conservation, recovery of reverse flow of the Tonle Sap Lake, etc. It is therefore proposed that additional joint studies are undertaken to support these processes.
- **More capacity building plan**. Coordinated operational management, integrated flood and drought management strategies and water governance should be based on sound science and a common understanding of the LMRB. There is consequently a need for educated water and related policy makers, managers, engineers and scientists. It is therefore recommended that a capacity building strategy is formulated that addresses the knowledge, understanding and capacity gaps. This should include all aspects of water resources management and include formal (post-graduate and diploma) courses as well as informal training courses.

1 INTRODUCTION

1.1 Background

Located in a monsoon climate, the Lancang-Mekong River Basin[1] (LMRB) is endowed with geographic advantages by crossing various ecological zones in China, Myanmar, Lao PDR, Thailand, Cambodia, and Viet Nam (**Figure 1**). The upper reach of this transboundary river is called the Lancang River, which is characterised by steep slopes and rapidly flowing waters, while the lower reach, known as the Mekong River, has a shallower slope and slower flowing reaches interspersed with rapids. The Lancang-Mekong River (LMR) supports the livelihoods of millions of people, including local communities, who depend on the river for their livelihoods, but also populations and economies outside of the LMRB, who rely on electrical energy produced within the basin. The riparian countries have harnessed the river system for various purposes, such as developing water infrastructure for irrigation, flood prevention, and electricity generation. Water resource development has, therefore, increased significantly over the last decade. These developments, while increasing the total volume of water available for development, have inevitably led to changes in the flow regimes, ecological functioning, and water quality of the Basin.

According to the newly released Global Climate Risk Index, countries along the Lancang-Mekong River, such as Myanmar, Viet Nam, and Thailand, are among the top 20 countries facing significant climate risks. The latest IPCC report also indicates a strong signal of intensifying flood and drought in the Southeast Asian region (IPCC WG1, 2021). Statistics show that severe drought occurs once every three years in the middle and lower reaches of Yunnan, China, with widespread impacts, and agriculture is among the worst affected. The LMRB witnessed persistent droughts in 2015–2016 and 2019–2020 and large floods in 1996 and 2000. These have severely impacted people's lives and livelihoods, causing substantial economic losses. These floods and droughts significantly threaten the riparian countries' capacity to realise the United Nations 2030 Sustainable Development Goals (SDGs). Several studies show that the severity and frequency of floods and droughts are driven by global climate change. Climate and hydrological model projections show that the warming climate would bring more intense precipitation, increasing the frequency and magnitude of future floods, while more intense El Nino events, also driven by climate change, increase the severity and frequency of droughts.

These extreme events, combined with the hydrological alterations due to increased water resource development, are altering the natural rhythm of the LMR's flow regime and its important floodplains, such as the Tonle Sap Lake. Generally, the hydrology of the LMR is influenced by two primary drivers, i.e., climate change and human activities. Developing a common understanding of the relative contributions of these drivers is critical to improved cooperation toward increasing climate resilience across the whole basin. Joint operations of storage can alleviate the impacts of floods and droughts while providing water, energy, and food security for riparian countries. There is already evidence that a better understanding of the meteorological and hydrological impacts of climate change will benefit the region. In 2016 a historically severe drought led to low flows and increased saltwater intrusion into the Mekong Delta. In response to the request from downstream countries, China implemented an emergency water supplement from its cascade reservoirs in the Lancang River, increasing the water

1 The Lancang-Mekong River/Basin is simply the Mekong River/Basin, composing of two parts: the Upper Mekong River/Basin (Lancang River/Basin in China) and Lower Mekong River/Basin. Exceptionally, in this document, the Lower Mekong River/Basin refers to the Mekong River/Basin.

discharge from Yunnan’s Jinghong Reservoir. This increased water levels along the Mekong mainstream and decreased salinity intrusion in the Mekong Delta. Similarly, drought in 2019 led to the lowest recorded water levels in the middle reaches of the Mekong mainstream, prompting similar releases from storage on the Lancang reach.

Climate change and development of the LMRB, therefore, pose severe challenges to the sustainable and fair development of the basin. But this also presents new opportunities to support regional development and mitigate climate change’s impacts. A deeper and shared understanding of the drivers behind changing hydrological conditions is critical and serves as the first step towards addressing the challenges through improved cooperation mechanisms among the riparian countries. This current joint initiative between the LMC Water Centre and MRC aims at developing this shared understanding.

Building on past fruitful collaborative studies such as the 2016 “Joint Observation and Evaluation of the Emergency Water Supplement from China to the Mekong River” and 2019 Joint Research project “Hydrological Impacts of the Lancang hydropower Cascade on Downstream Extreme Events,” and to advance joint activities following the signing of the Memorandum of Understanding (MOU) between the LMC Water Center and MRCS in December 2019. Through this MOU, the LMC Water Center and MRCS jointly proposed a “Joint Study on the Changing Pattern of Hydrological Conditions of the LMRB and Adaption Strategies”. This was intended to allow the riparian countries to respond better to flood and drought risks exacerbated by climate change and water resources development by providing recommendations for joint actions at river basin and country levels. This study also aligns with the decisions of the LMC Joint Working Group and MRC Joint Committee.

1.2 The origin of this current study

At a special meeting of the Joint Working Group (LMC JWG) on the Lancang-Mekong Water Resources Cooperation, organised by Thailand in early August 2019, the parties reached a consensus on the primary causes of the 2019 extreme low flows, agreeing that these were primarily due to reduced rainfall in the basin, which was in turn due to the El Niño phenomenon. The MRC Joint Committee (JC) special session held in Vientiane on 5 November 2019 discussed the drought and low flow situation and tasked the MRCS to analyse the causes of the situation further and make recommendations for further work. Research findings of several Chinese institutes were reported by the Lancang-Mekong Water Resources Cooperation Center (LMC Water Center) at the Second Virtual Meeting of the LMC JWG held on 24 September 2020. The LMC JWG noted these observations and agreed to strengthen cooperation between the riparian countries and improve coordination through further joint studies. All riparian countries are expected to participate in these joint studies and work together to promote mutual understanding and coordinated response to floods, droughts, and other water issues driven by changing climate and development of the basin.

Recently China took the initiative to provide year-round hydrological information starting from 1 November 2020, at two hydrological stations Yun Jinghong and Man’an, on the Lancang River, to the other five riparian countries and the MRCS. This will enhance basin-wide cooperation toward addressing climate extremes and minimising the impacts along the Mekong mainstream. The six-member countries of the LMC have also agreed to further enhance the sharing of water resources data, information, knowledge, experience, and technologies through the establishment of the Lancang-Mekong Water Resources Cooperation Information Sharing Platform. This platform is expected to promote the sustainable development, management, and conservation of water and related resources in the member countries.

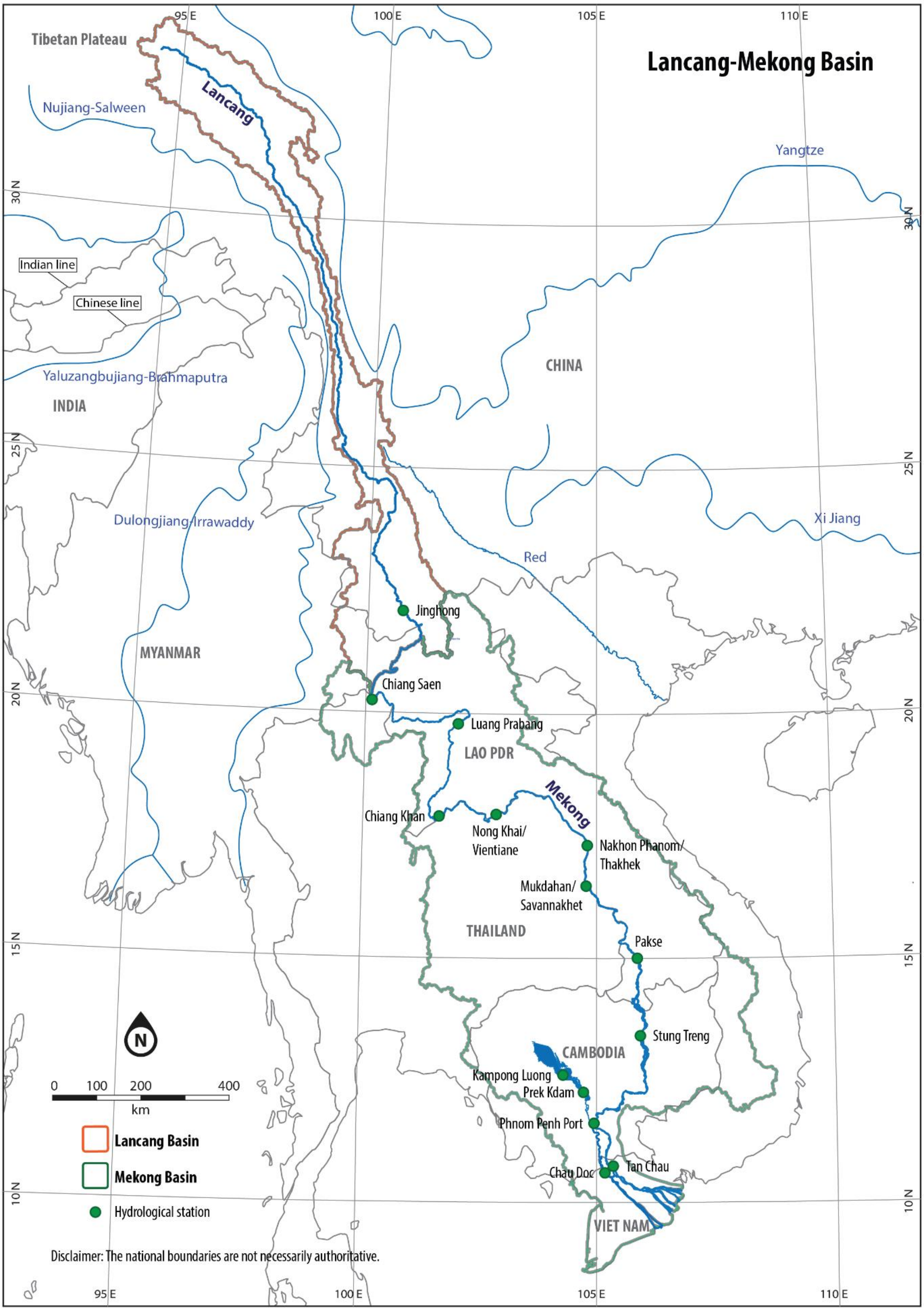

Figure 1. Map of the Lancang-Mekong Basin. The Lancang-Mekong Basin is composed of two parts: the Upper Mekong Basin (Lancang Basin in China) and the Lower Mekong Basin (downstream of China)

1.3 Objectives

The **objective of the Joint Study** is to provide a better and common understanding of hydrological changes in the LMRB due to climate change and developments such as land use changes, hydropower development, and operations and irrigation. The study then aims to provide insights into strategies to assist the riparian States in adapting to climate change in the basin. The following main achievements are expected:

- Identification, attribution, and forecasting of patterns in the hydrological conditions in the LMRB using available data and information from the whole basin.
- Develop a common understanding of the relative contributions of meteorological conditions and the development of storage on flows in the Mekong mainstream.
- Formulation of advice on short-term, medium-term, and long-term measures to adapt to the changing hydrological conditions through enhanced cooperation, including structural and non-structural measures (as well as Nature-based Solutions, NbS), to improve people's wellbeing in the LMRB.

1.4 Scope of the Joint Study

The Joint Study has three components:

- **Component 1**: To assess historical changes in the hydrological conditions and the causes of these changes.
- **Component 2**: To forecast future trends in hydrological conditions under climate change and water resource development scenarios.
- **Component 3**: To propose climate change adaptation strategies to help the riparian States cope with the changing hydrological conditions.

The hydrological characteristics to be investigated include natural runoff composition, flood and drought of the Lancang-Mekong River Basin, and reverse flow of the Tonle Sap River. The study will be implemented in two phases:

- **Phase 1 (2022)**: Component 1 will be implemented first, focusing on historical changes in the hydrological conditions and the causes using available data/information and models, and make preliminary recommendations about short-term strategies, such as enhanced sharing of data, better/timely notifications, and opportunities for improving the joint operation of existing water infrastructures.
- **Phase 2 (2023–2024)**: Components 2 and 3 will be implemented, covering future trends and medium-and long-term adaptation strategies.

1.5 Principles of Cooperation

Through the MOU, the LMC Water Center and MRCS have committed to the following values and principles of cooperation, as shown in **Figure 2**:

- **Mutual Commitment**: Agreeing on the collective objectives and benefits of the Joint Study is the first step towards good faith commitments to cooperate. The MOU, therefore, encourages both parties to share and exchange data, information, models, and assessments. Active participation in the analysis of trends, causes, and impact will foster accountability and ownership. Both parties are committed to meeting the deadlines of the deliverables of the Joint Study.

- **Trust**: Transparency and clear communication between both parties to gain clarity and understanding strengthen trust during the study implementation. A trustful relationship increases ownership of the results and recommendations of the Joint Study. Both parties may have different views on the specific results but are willing to work together to investigate further, improve common understanding, and reach an agreement.
- **Joint Success**: The recommendations of the Joint Study are the most critical outcome of the study. Joint success, therefore, aims to promote the recommendations of the Joint Study to take immediate action. Therefore, having a sustained collective interest in working toward a '**Shared Knowledge Platform**,' where data, information, models, and knowledge can be exchanged, is a start of joint success. This will foster mutual benefits beyond the study to share more information, enhance notification, and work towards the coordinated operation of water facilities and better address basin-wide flood and drought risks, and jointly monitor and report the hydrological state of the whole basin.

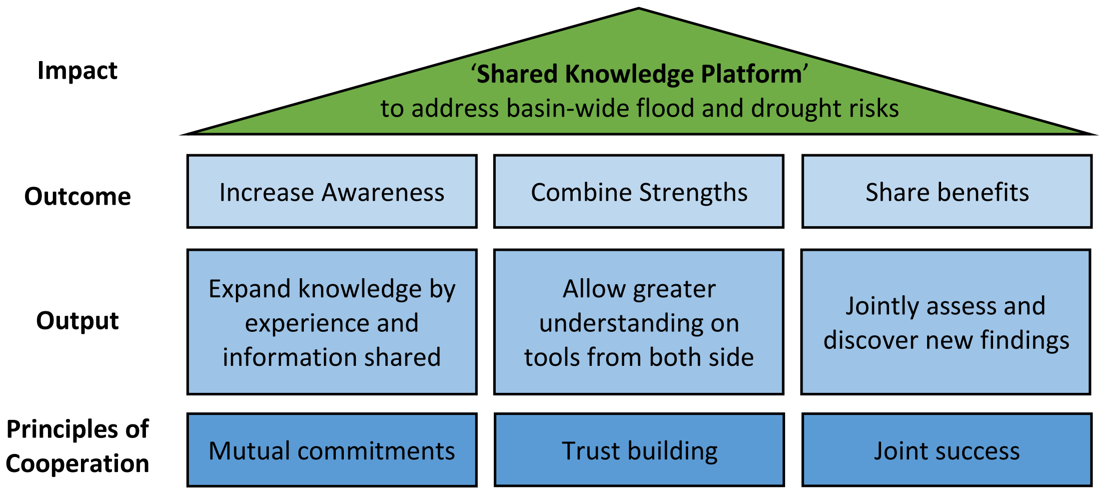

Figure 2. Principles of cooperation between the LMC Water Center and MRCS

2 DATA AND METHODOLOGY

2.1 Spatial and temporal coverage

The Joint Study Phase 1 primarily focuses on the Lancang-Mekong River Basin as a whole, including hydrological monitoring and modelling across the entire Basin. However, the hydrological impact assessment is specifically concentrated on the Lancang-Mekong mainstream and the Tonle Sap Lake.

The Joint Study Phase 1 covers a temporal period of 40 years, from 1980 to 2020. In order to conduct a comprehensive analysis of historical changes in featured hydrological conditions and their causes, it is important to identify the tipping point based on the time series of streamflow observations. We conducted the Pettitt test on the annual average time series at Chiang Sean for the period of 1980 to 2020 and identified the year 2009 as the abrupt changing point. Further comparative analysis was carried out on the length of time series before and after the changing-point year, and minor differences were found between the 1980-2009 series and 2000-2009 series[2]. For ease of understanding by a wider audience and to balance the time series length, the study period is divided into two sub-periods: (1) 2000 to 2009, and (2) 2010 to 2020. More details can be found in Annex A – Identification of break year of abrupt changes in hydrological pattern.

The chosen period for analysis of the long-term trend of drought characteristics and driving factors spans from 1901 to 2020 with specific attention to 2000-2020.

2.2 Datasets

Datasets used for the Joint Study Phase 1 are elaborated below. **Figure 3** shows the location of rainfall stations. **Figure 4** illustrates the location of the key hydrological stations for flow monitoring on the Lancang-Mekong mainstream. **Table 1** presents the characteristics of the key stations for hydrological analysis for the Lancang-Mekong mainstream and Tonle Sap Lake.

2.2.1 Datasets for THREW hydrological model

The sub-catchments of the LMRB for THREW hydrological model were derived from 1 km x 1 km Digital Elevation Model (DEM). The soil hydraulic parameters were extracted from the soil classification data from the 10 km global digital soil map provided by the Food and Agriculture Organization of the United Nations (FAO). The MODIS dataset of a spatial resolution of 500 m × 500 m and a temporal resolution of 16 days was used for the Leaf Area Index (LAI) data, the Normalized Difference Vegetation Index (NDVI) data, and the snow cover data.

The main inputs to the THREW model were daily rainfall from 105 stations (**Figure 3**) and potential evapotranspiration from 32 meteorological stations. The observed discharge from nine hydrological

[2] MRCS's experience suggests that there are no significant hydrological changes observed between 1985 and 2009. Therefore, the period of 2000-2009 was chosen to represent the condition before major changes. Additionally, this is evident in findings of Lu and Chua (2021) River Discharge and Water Level Changes in the Mekong River: Droughts in an Era of Mega-Dams. Hydrological Processes, 35(7), e14265. https://doi.org/10.1002/hyp.14265 and Timo et al. (2017) Observed river discharge due to hydropower operations in the Upper Mekong Basin. Journal of Hydrology, 545(28-41). http://dx.doi.org/10.1016/j.jhydrol.2016.12.023

stations (Figure 4 and Table 1) along the Lancang-Mekong mainstream was utilised for model calibration and validation.

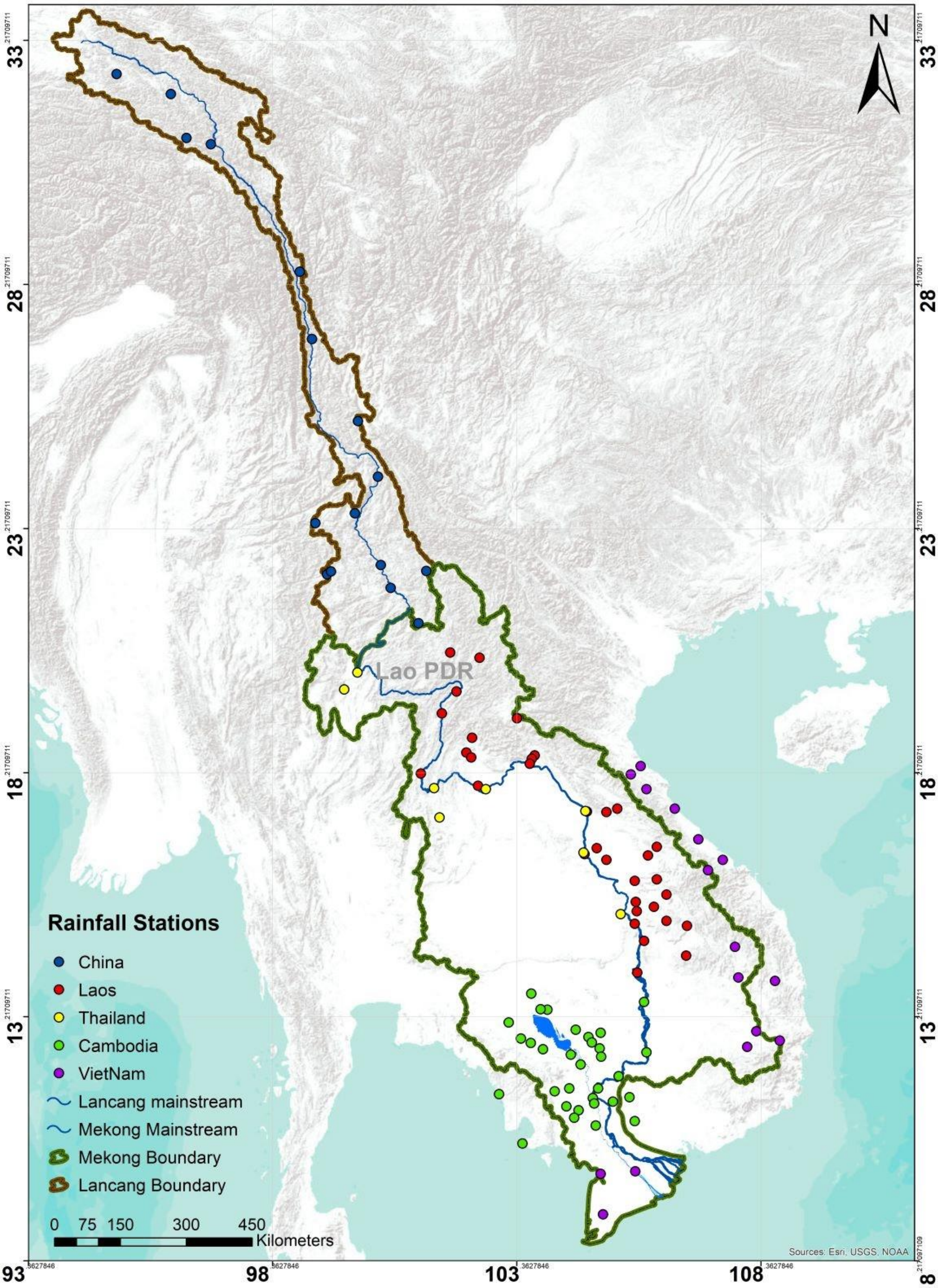

Figure 3. Rainfall stations used in hydrological models of THREW and SWAT

Figure 4. Location of key hydrological stations for flow monitoring on the Mekong mainstream

Table 1. Characteristics of the key stations for hydrological analysis for the Lancang-Mekong mainstream and Tonle Sap Lake

No	Station	River	River length	Catchment area	Cumulative area	Hydro-geographical features
1	Jinghong (China)	Lancang	2,707 km	143,647 km^2	143,647 km^2	Only hydrological station on the Lancang River
2	Chiang Saen (Thailand)	Mekong	2,364 km	49,477 km^2	193,124 km^2	Recognised as a transboundary station between Lancang and Mekong River
3	Luang Prabang (Lao PDR)	Mekong	2,010 km	84,339 km^2	277,463 km^2	Key station upstream of Xayaburi
4	Chiang Khan (Thailand)	Mekong	1,715 km	22,216 km^2	299,679 km^2	Key station downstream of Xayaburi
5	Nong Khai/Vientiane (Thailand/Lao PDR)	Mekong	1,549 km	10,586 km^2	310,265 km^2	Key station at Lao Capital City
6	Nakhon Phanom/Thakhek (Thailand/Lao PDR)	Mekong	1,221 km	68,691 km^2	378,956 km^2	Key station downstream of Vientiane
7	Mukdahan/Savannakhet (Thailand/Lao PDR)	Mekong	1,128 km	16,208 km^2	395,164 km^2	Upstream of Kong-Chi-Mun confluence
8	Pakse (Lao PDR)	Mekong	866 km	158,058 km^2	553,221 km^2	Downstream of Kong-Chi-Mun confluence
9	Stung Treng (Cambodia)	Mekong	683 km	90,016 km^2	643,237 km^2	Transboundary flow monitoring for Lao PDR and Cambodia
10	Phnom Penh Port (Cambodia)	Tonle Sap	–	99,965 km^2	743,202 km^2	Key station for reverse flow to the Tonle Sap Lake
11	Prek Kdam (Cambodia)	Tonle Sap	–	–	–	Key station for reverse flow to the Tonle Sap Lake

No	Station	River	River length	Catchment area	Cumulative area	Hydro-geographical features
12	Kampong Luong (Cambodia)	Tonle Sap Lake	–	–	–	Key station for reverse flow to the Tonle Sap Lake
13	Tan Chau (Viet Nam)	Mekong	–	66,777 km^2	809,980 km^2	Transboundary flow monitoring for Cambodia and Viet Nam
14	Chau Doc (Viet Nam)	Bassac	–	–	–	Transboundary flow monitoring for Cambodia and Viet Nam

2.2.2 Datasets for SWAT hydrological model

Daily rainfall and climatic data such as maximum and minimum air temperatures, relative humidity, solar radiation, and wind speed are the main inputs for the SWAT model, while discharge records at the key stations along Mekong mainstream (from Chiang Saen to Kratie) and some tributaries are used for the calibration and validation of the model. The existing SWAT model for the Mekong River Basin from the MRC Council Study was updated to extend the simulation period up to 2020 with MRC hydrometeorological datasets and additional national datasets from the Member Countries.

For the Lancang River Basin, precipitation and climatic data from 17 stations (**Figure 3**) were downloaded from the Global Summary of the Day (GSOD) of the National Oceanic and Atmospheric Administration[3] (NOAA) of the United States.

Four main spatial datasets for topographic data or Digital Elevation Model (DEM) with 50 m resolution, river network in 2010, land use in 2002/2003, and soil type in 2002 of global data source and MRC source for the Mekong River Basin were used for SWAT model setup, sub-basin delineation and hydrological response units (HRUs) generation.

2.2.3 Datasets for the Source water system simulation

The datasets required to run the schematic water system model in Source for hydrological modelling and impact assessment are:

- Daily discharge is exported from SWAT and applied at inflow nodes for the period of 1985–2020.
- Daily observed rainfall is interpolated for SWAT sub-catchments using Nearest Neighbour and Thiessen algorithms in SWAT. Interpolated daily rainfall is applied at storage and water user nodes for 1985–2020.
- Potential Evapotranspiration (PET) is estimated using daily climate variables (such as temperature and wind speed etc.) and based on the Penman–Monteith algorithm in SWAT. Daily PET is also applied at storage and water user nodes for 1985–2020.
- Daily observed discharge at eight key hydrological stations (on the Mekong mainstream, as shown in **Figure 4**) is available at gauge nodes for 1985–2020. Observed discharge is also used to compare with the modelled discharge and determine the model performance.

In addition, the water use dataset from the MRC Council Study, associated with the updated MRC Irrigation Database in 2018 and Hydropower Database in 2021, was used as water use condition in 2020 for water system simulation in the Source model. The dataset provides input required by water system modelling, such as hydropower characteristics, irrigation projects, and estimated domestic/industrial water use in the Mekong River Basin.

The existing general rule curves of hydropower projects were taken from the MRC Basin Development Plan (BDP) in 2007. However, the Source model introduced a new capability to set bespoke operating rules for each year and each hydropower project. The updated rule curves enabled by this new approach may allow the Source model to more realistically capture the key hydropower components, such as changes in the volume storage of large reservoirs. Moreover, changes in the type of hydropower

[3] https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00516, access in 2013 for first SWAT setup, in 2018 for second update, and in 2021 for third update.

operations based on seasonal forecasts may be possible. This can simulate changing hydropower operations based on the risks to generation capacity.

Furthermore, related information for irrigation projects, such as crop pattern, crop calendar, pump capacity, and irrigation efficiency, were retrieved from the MRC Water Utilisation Program (WUP) in 2003 and the MRC Basin Development Plan (BDP) in 2007.

2.2.4 Datasets for drought study

For analysis of the drought conditions over the LMRB, four datasets were considered below, and a summary of these datasets is in **Table 2**:

- The **Climate Research Unit gridded Time Series** (**CRU TS**) global reanalysis meteorological dataset was chosen for the drought analysis. CRU TS is one of the most widely used observed climate datasets and is produced by the UK's National Centre for Atmospheric Science (NCAS) at the University of East Anglia's Climatic Research Unit (CRU). CRU TS provides monthly data on a 0.5°×0.5° grid covering global land surfaces (excluding Antarctica) from 1901 to 2021. There are ten variables, all based on near-surface measurements: temperature (mean, minimum, maximum, and diurnal range), precipitation (total, also rain day counts), humidity (as vapour pressure), frost day counts, cloud cover, and potential evapotranspiration. It has been widely used in meteorological and hydrological studies (Harris et al., 2020). Based on the CRU TS dataset, this study extracted the precipitation and potential evapotranspiration data of the LMRB in the past 121 years (1901–2021).
- Provided by the **European Centre for Medium-Range Weather Forecasts** (**ECMWF**), **ERA5-Land** offers worldwide, hourly, high-resolution data for a more accurate representation of the water and energy cycles (Muñoz-Sabater et al., 2021). Hourly data with a spatial resolution of 0.1° is available. Previous studies show that the temperature and precipitation biases in ERA5-Land are consistently lower than in other reanalysis products (e.g., ERA-Interim, Tarek et al. (2020)). Nogueira (2020) shows the rainfall anomalies correlation is around 0.9–1.0 in the entire LMRB region, making it reasonable to derive drought indexes, i.e., SPI and SPEI. In this study, we use four variables, i.e., total precipitation (in mm), 2-m temperature (in K), 10-m wind (in both the eastward and northward component of the 10-m wind; in m/s) in the past 72 years (1950–2021).
- **Climate Hazards Group InfraRed Precipitation with Station data** (**CHIRPS**[4]) was created in collaboration with scientists at the USGS Earth Resources Observation and Science (EROS) Center to deliver complete, reliable, up-to-date datasets for several early warning objectives, like trend analysis and seasonal drought monitoring. CHIRPS is a 35-year quasi-global rainfall dataset. Spanning 50°S–50°N (and all longitudes) and ranging from 1981 to near-present, CHIRPS incorporates climatology, CHPclim, 0.05° or 5 km resolution satellite imagery, and in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring.
- **El Niño indicator**[5] (Nino 3.4) is defined as the average Sea Surface Temperature (SST) anomalies in the Nino 3.4 region (170°E–120°W, 5°S–5°N). NOAA (National Oceanic and Atmospheric Administration, USA) uses the 3-month running average Nino 3.4 as an indicator for an incidence of ENSO (El Niño Southern Oscillation) event. The 3-month overlapping mean

[4] https://www.chc.ucsb.edu/data/chirps

[5] https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

anomaly is calculated by comparing the 3-month overlapping mean with the single fixed base period that is, the mean of the specified 30-year SST, which evolves every five years, so values during 1950–1955 will be based on the 1936–1965 base period, values during 1956–1960 will be based on the 1941–1970 base period, and so on and so forth. The monthly Niño-3.4 index that uses these new centered 30-year base periods[6] is used in this research.

The drought study covers the entire Lancang-Mekong River Basin from 1901 to 2021; however, a selection of the results for 2000–2020 is reported for Phase 1 of the Joint Study.

Table 2. Datasets for drought analysis

No	Dataset	Variables	Spatial resolution	Data availability
1	CRU TS	Precipitation potential evapotranspiration	0.5°	1901–2021
2	ERA5-Land	Total precipitation 2-m temperature 10-m wind	0.1°	1950–2021
3	CHIRPS	Precipitation	0.05°	1981–2020
4	Nino 3.4	–	–	1950–2021

2.2.5 Data exchange and sharing

The LMC Water Center and MRC have committed to continuously increasing cooperation as outlined in the principles of cooperation in the MOU. The following datasets were, therefore, exchanged to refine the models and provide additional support to technical analyses.

Data sharing from LMC Water Center

LMC Water Center has shared the following data with MRC (Annex B – Data sharing from LMC Water Center)

- Average daily temperature data from 1991 to 2020 of 16 stations in the Lancang River.
- Daily precipitation data from 1961 to 2020 of 16 stations in the Lancang River.
- Characteristics of storage on the Lancang River.

The following data has also been shared from China with MRC in previous joint research and used in this Joint Study:

- Flood season hydrological data at Jinghong station from 2002 to 2020.
- Year-round hydrological data at Jinghong station since November 2020.
- Daily water level and discharge data from 1 December 2015 to 15 May 2016 at Jinghong station.
- Long term average monthly data of water level and discharge for 1960 to 2009 and 2010 to 2015 at Jinghong station.
- Monthly water level and discharge at Jinghong from October 2009 to May 2010 and from October 2012 to May 2013.
- Daily water level and discharge at Jinghong station from December 2013 to January 2014.

[6] https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_change.shtml

Data sharing from MRC

MRC has shared the following data (Annex C – Data sharing from MRC):

- Daily discharge data from 2017 to 2022 at six stations along the Mekong mainstream (Chiang Saen, Nong Khai, Mukdahan, Khong Chiam, Pakse, and Stung Treng) and 1985 to 2022 of Chiang Khan Station.
- Maximum and minimum daily temperature data from 1980 to 2020 for 19 stations in the Lower Mekong Basin.
- Daily precipitation data from 1980 to 2020 of 89 stations in the Lower Mekong Basin.

2.3 Models and tools

2.3.1 Methodology to study the changing patterns and their causes

Significant effort was extended to investigate hydrological characteristics, including natural runoff composition in the LMRB, seasonal distribution of streamflow, its pattern during 2000-2009 and its change during the period of 2010–2020, the separating causes from climate change and human activities, drought, and flood pulse phenomenon associated with Tonle Sap Lake.

The Study Team jointly selected the **THREW** and **SWAT** models for hydrological modelling and the **Source** model for water system modelling. The calibration and setup of the three models were openly shared to ensure a high-quality analysis. The modeling framework and analysis approach is illustrated in **Figure 5**. More details of characteristics of the three models are given in **Table 3**.

Implementing the Joint Study allows the LMC Water Center and MRCS to explore the opportunity to establish a **'Shared Knowledge Platform'** by exchanging data, information, and proposed models. The assessment and knowledge acquired during the project can be further disseminated through workshops/seminars and shared training sessions.

More specifically, the following methods were adopted to assess the relative contributions of climate and development to the hydrology of the LMRB:

- **Spatio-temporal flow distribution on the Lancang-Mekong River**: The two hydrological models (THREW and SWAT) were used to explore the spatio-temporal flow distribution along the LMR mainstream. The model parameters were calibrated/validated against the available streamflow data for nine hydrological stations. To distinguish the impacts from those caused by the development of the basin, the hydrological models were run both with (developed) and without (naturalised) the storage and abstractions for 2010–2020. The difference between these simulations for 2010–2020 represents the effect of development on streamflow. Comparison of the naturalised streamflow data provides an indication of the impacts of the severe droughts from 2010 to 2020. Furthermore, the Source model was configured to simulate flows with and without development in the basin.
- **Flood pulse of the Tonle Sap Lake**: The reverse flows to the Tonle Sap Lake were estimated by available observed water level data at Phnom Penh Port, Prek Kdam, and Kampong Luong. The accumulated reverse flows (average, minimum, and maximum) for 2000 to 2009 and 2010–2020 were used to present the changes.
- **Meteorological drought over Lancang-Mekong River Basin**: The Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI) were used to analyse

the meteorological drought trends in the LMRB. The following methods were applied: From 1901–2021, the analysis was based on CRU TS data; and from 1950–2021, the analysis was based on ERA5-Land data. These two periods provide a comprehensive picture of the evolution of drought patterns in the basin. To capture the impacts of meteorological drought, the drought matrix (frequency, duration, and severity) from 2000 to 2009 was compared to 2010 to 2020.

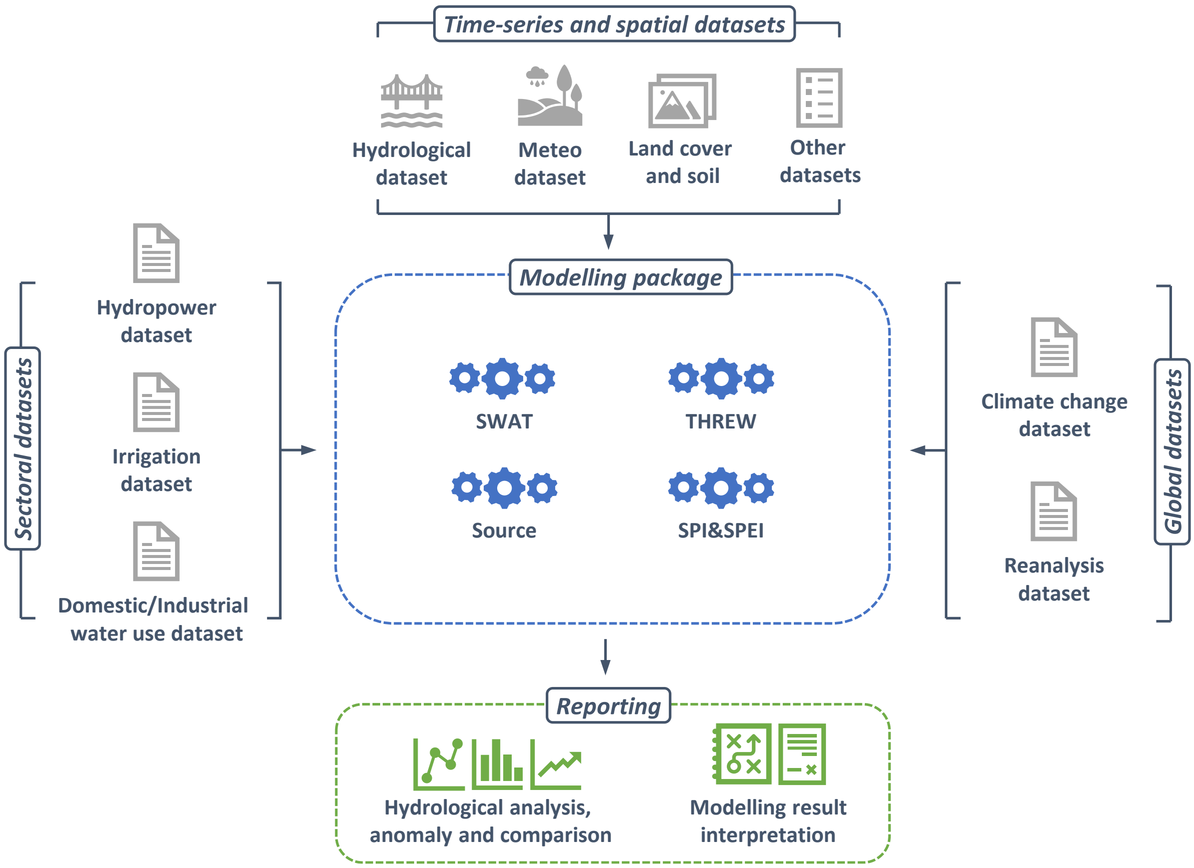

Figure 5. Modelling framework and analysis approach for Phase 1 of the Joint Study

2.3.2 Tsinghua Hydrological Model Based on Representative Elementary Watershed (THREW)

The THREW model has been developed to simulate streamflow in the LMRB. By considering the basin's spatial diversity, the THREW model divides a basin into well-defined sub-basins, which are representative elementary watersheds (REWs). Each REW is separated into several zones that can reflect different underlying surface types. The REWs and zones are linked by a set of balance equations for mass, momentum, energy, and entropy, including associated constitutive relationships for various exchange fluxes.

The THREW model discretized the basin into REWs, and each of the REW is further divided into eight sub-zones: (1) snow-covered zone (n-zone), (2) saturated zone (s-zone), (3) unsaturated zone (u-zone), (4) vegetable covered zone (v-zone), (5) bared zone (b-zone), (6) sub-stream network zone (t-zone), (7) glacier-covered zone (g-zone) and (8) main channel reach zone (r-zone).

Vegetation, snow, soil ice, and glacier ice are added to the existing system (water, gas, and soil matrix). As a result, energy-related processes, i.e., evaporation/transpiration occurring from various kinds of land cover and hydrological phenomena (especially related to the cold region such as accumulation and depletion of snowpack and glacier, and freezing and thawing of the soil ice), can be modelled in a physically reasonable way. More details on the THREW model can be found in Annex D – Tsinghua Hydrological Model Based on Representative Elementary Watershed (THREW).

The THREW model has been successfully applied to many watersheds across China, the United States, and Europe and simulates the hydrological processes in the LMRB during the period of analysis quite well. In this study, the THREW model was applied to simulate the rainfall-runoff process in the LMRB, which is divided into 651 REWs, as shown in **Figure 6**.

The daily runoff data for 1985–2009 at nine hydrological stations (**Figure 4**) along the Lancang-Mekong mainstream were used for model calibrating and validating. The model was calibrated separately for the wet season (June to November) and dry season (December to May). Then, the simulated discharge for the two periods was combined to produce a complete time series. The calibration process was conducted from upstream to downstream for each sub-catchment. Once the calibration was finished at an upstream station, the parameters for the REWs draining to this station were fixed. The discharge of the next downstream station was then used to calibrate the parameters for the REWs located in the inter-region between the two stations. The whole period of 1985 to 2009 was divided into two sub-periods used for model calibration (2000–2009) and validation (1985–1999), respectively. The results of calibration and validation at key stations on the Mekong mainstream are summarized in **Table 4**. More detailed results are shown in **Figure D-3**.

2.3.3 Soil and Water Assessment Tool (SWAT)

Soil and Water Assessment Tool (SWAT) is a physically based, semi-distributed hydrologic model that has been widely used to understand water quantity and quality issues (sediment, nutrients, chemical, and bacterial transport) over a wide range of watershed scales resulting from the interaction among weather conditions, soil properties, stream channel characteristics, vegetation and crop cover, and land-management practices. The SWAT model divides a watershed into sub-watersheds, further subdivided into hydrological response units (HRUs) consisting of homogeneous land-use, soil, and slope characteristics.

The SWAT system is linked to geographical information system (GIS) to integrate various spatial environmental data such as land use, soil type, and digital elevation model (DEM). The SWAT model provides two methods for computing surface runoff volume for each HRU: the Soil Conservation Service curve number[7]. Flow is routed in the channel using the Muskingum routing method or a variable storage coefficient method. Groundwater flow contributing to stream networks is calculated by creating shallow aquifer storage, and percolation from the bottom of the root zone is considered as recharge to the shallow aquifer.

There are three methods used to estimate the potential evapotranspiration in SWAT: Priestley and Taylor, Penman–Monteith and Hargreaves, and Samani. The theory and details of the hydrological processes of the SWAT model are available online in the SWAT documentation[8]. The SWAT model has been one of the main rainfall-runoff models applied in the MRC DSF. A Schematic of the SWAT model setup for the LMRB is presented in **Figure 6**. The performance of the SWAT model is presented in **Table 4**.

7 United States Department of Agriculture (USDA) Soil Conservation Service, 1972.

8 http://swatmodel.tamu.edu/

Annex E – Soil and Water Assessment Tool (SWAT) discusses more detail on the SWAT model, its governing processes, and calibration/validation performance.

2.3.4 Using Source for water system simulation

The Source model is a whole river system modelling framework designed to support the needs of Integrated Water Resource Management (IWRM). The schematic water system Source model used for this study is based on a model prepared for the MRC Council Study.

This model encompasses the Lancang and Mekong Basins, the downstream outlet being the gauge on the Mekong River at Kratie, Cambodia. It represents the Mekong River flow network, including major tributaries, and simulates reservoirs, hydropower generation, and water use for agriculture and domestic purposes. The Source model of the physical river network and streamflow routing is a direct conversion from the MRC IQQM model.

A general description of the Source model can be found in Annex F – Source, Hydrological Modelling Platform.

During the MRC Council Study in 2017, the Source model demonstrated its capability to support the MRC DSF modelling package in dealing with hydropower operations, irrigation water demand, and domestic/industrial water demands. In particular, the Source model has the capability to either activate or deactivate the hydropower/irrigation modules to differentiate their hydrological impacts from natural changes in hydrology. The Source model needs inputs from the SWAT outputs on a sub-basin scale for precipitation, potential evapotranspiration, and discharge.

The MRC Council Study used a consistent set of agreed scenarios intended to enable the complete assessment of environmental and socio-economic impacts associated with water resources development in six development sectors for the Mekong River Basin. The six thematic sectors include hydropower, irrigation, agriculture, and land use change, domestic and industrial water use, navigation, and flood protection. This complete assessment is achieved through a set of main scenarios M1 for Early Development, M2 for Development 2020, and then M3 for Development 2040 with and without climate change impacts. Sub-scenarios for each water sector then test changes resulting from drivers of change to assess the changes due to that sector. The future scenario M2 with 2020 Development has been applied in the Joint Study, as depicted in **Figure 6**. The performance of the Source model is shown in **Table 4**.

The long-term simulation for the MRC Council Study used a 24-year (1985–2008) record of reference climatic conditions to give the full range of high and low flow years and the likelihood of occurrence using statistical analysis. The near future scenario (M2) used the same climate input as the reference climate while considering the whole range of likely water resource developments in the context of other changes, such as urbanisation and economic growth up to 2020. However, for the Joint Study, the M2 model has been extended to include hydrological inputs to 2020.

Table 3. Summary of model characteristics for the Joint Study–Phase 1

Model characteristics	THREW	SWAT	Source
Datasets			
Rainfall	Parameter: Daily observed rainfall at 105 rain gauges Period: 1980–2020 Source: MRCS and China Meteorological Administration (CMA)	Parameter: Daily observed rainfall at 229 stations Period: 1980–2020 Source: MRCS and National Dataset	Parameter: Daily observed station rainfall, interpolated for SWAT sub-catchments using Nearest Neighbour and Thiessen algorithms in SWAT Period: 1985–2020 Also applied at storage and water user nodes Source: MRCS
PET	Parameter: Daily potential evapotranspiration at 32 meteorological gauges Period: 1991–1999 Source: MRCS and China Meteorological Administration (CMA)	Parameter: Min/Max temperature to estimate potential evapotranspiration (PET) Period: 1980–2020 Source: MRCS and National Dataset	Parameter: Daily potential evapotranspiration- estimated using daily climate variables (e.g., temperature, wind speed, etc.) and Penman-Monteith equation for SWAT-sub-catchments in SWAT Period: 1985–2020 Also applied at storage and agricultural water user nodes Source: MRCS
Discharge	Parameter: Daily discharge at key hydrological stations Period: 1985–2020 Source: MRCS and Ministry of Water Resources of China	Parameter: Daily discharge at key hydrological stations Period: 1985–2020 Source: MRCS	Parameter: Daily discharge of SWAT-sub-catchments, imported from SWAT rainfall-runoff modelling Period: 1985–2020 Applied at inflow nodes Source: MRCS
Land cover	Land Cover: 8 classes (Ice/Snow, Water surface, Forest, Shrub, Grassland, Farmland, Wetland, and City) from MODIS (2001–2012)	Classification and its description: 17 classes (Agriculture, Aquaculture, Bamboo forest, Bare soil, Flooded forest, Forest, Forest	Land cover is part of the underlying SWAT modelling data inputs

Model characteristics	THREW	SWAT	Source
	NDVI, LAI, Snow Cover: MODIS Source: Center for Earth System Science, Tsinghua University (1982–2015)	plantation, Grassland, Mangrove, Marsh/Swamp area, Orchard/Industrial plantation, Other, Paddy rice, Shifting cultivation, Shrubland, Urban area, and Water body) Land Use/Land Cover 2003 Source: MRCS	Source: MRCS
Soil type	Soil: 13 types (Clay-heavy, Silty Clay, Clay, Silty Clay Loam, Clay Loam, Silt, Silt Loam, Sandy Clay, Loam, Sandy Clay Loam, Sandy Loam, Loamy Sand and Sand) Source: Food and Agriculture Organization of the United Nations (FAO)	Soil: 203 types Source: Food and Agriculture Organization of the United Nations (FAO) 2002	Soil types are part of the underlying SWAT modelling data inputs Source: MRCS
Digital Elevation Model	Spatial boundary: Entire Lancang-Mekong Basin above Phnom Penh Resolution: 1 km x 1 km Source: NASA's Shuttle Radar Topography Mission (SRTM)	Spatial boundary: Entire Lancang-Mekong Basin above Phnom Penh River network: Delineated by SWAT Model and MRCS Resolution: 50-meter Source: MRC and Japan International Cooperation Agency, 2005	Digital Elevation Model is part of the underlying SWAT modelling data inputs Source: MRCS
Water demands			
Hydropower demands	N/A	N/A	Rule curves as defined in the MRC Council Study model based on the M2 scenario (Development 2020) Source: MRCS A custom drawdown function is applied to Nuozhado and Xiaowan in the Lancang River basin.

Model characteristics	THREW	SWAT	Source
Irrigation demands	N/A	N/A	Irrigation schemes and storage in the Mekong River Basin from the MRC Council Study model based on the M2 scenario (Development 2020) Source: MRCS
Domestic and industrial demands	N/A	N/A	Domestic and industrial demands from the existing Council Study model based on the M2 scenario (Development 2020) Source: MRCS
Environmental demands	N/A	N/A	N/A
Model calibration/validation			
Model type	Semi-distributed hydrological model	Semi-distributed Hydrological model	Schematic water system model
Warm-up period	01 Jan 1996 to 31 Dec 1999 (4 years)	01 Jan 1980 to 31 Dec 1984 (5 years)	Calibration and validation are undertaken in the SWAT modelling
Calibration period	Hydrological period: 01 Jan 2000 to 31 Dec 2009 Water demand: N/A	Hydrological period: 01 Jan 1985 to 31 Dec 2008 Water demands: N/A	Calibration and validation are undertaken in the SWAT modelling
Validation period	Hydrological period: 01 Jan 1985 to 31 Dec 1999	Hydrological period: 01 Jan 2009 to 31 Dec 2020	Calibration and validation are undertaken in the SWAT modelling
Parameter and location	Simulated and observed flow at nine key hydrological stations on the Mekong mainstream: Jinghong, Chiang Saen, Luang Prabang, Chiang Khan, Nong Khai, Nakhon Phanom, Mukdahan, Pakse, and Stung Treng	Simulated and observed flow at eight key hydrological stations on the Mekong mainstream: Chiang Saen, Luang Prabang, Chiang Khan, Nong Khai, Nakhon Phanom, Mukdahan, Pakse, and Stung Treng	Calibrated flows and observed discharge at eight key hydrological stations are provided by the MRC SWAT model and applied directly at inflow nodes in the Source model
Model results	Daily discharge	Daily discharge	Daily discharge

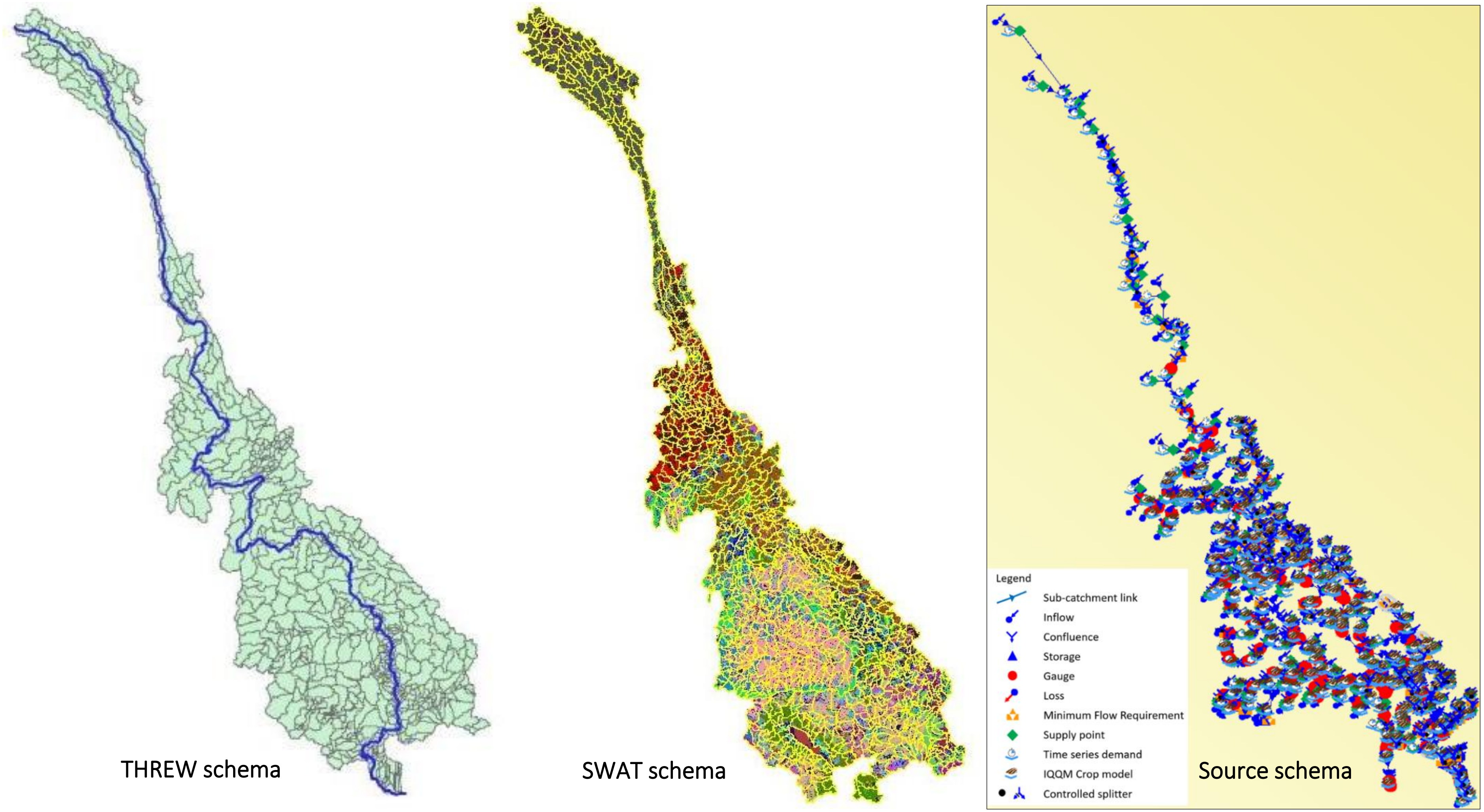

Figure 6. Schematic layout of the three models used in the Joint Study Phase 1: THREW, SWAT and Source

Table 4. Performance of the three models used for the Joint Study Phase 1

Model performance		THREW		SWAT		Source	
Performance for calibration		**Period: 2000–2009**		**Period: 1985–2008**		**Period: 2000–2009 (only statistic, no calibration)**	
1	Jinghong (China)	NSE Daily: NSE Monthly:	0.80 0.87	NSE Daily: NSE Monthly:	– –	NSE* Daily: NSE Monthly:	– –
2	Chiang Saen (Thailand)	NSE Daily: NSE Monthly:	0.80 0.84	NSE Daily: NSE Monthly:	0.83 0.92	NSE Daily: NSE Monthly:	0.87 0.94
3	Luang Prabang (Lao PDR)	NSE Daily: NSE Monthly:	0.89 0.93	NSE Daily: NSE Monthly:	0.81 0.93	NSE Daily: NSE Monthly:	0.86 0.94
4	Chiang Khan (Thailand)	NSE Daily: NSE Monthly:	0.90 0.93	NSE Daily: NSE Monthly:	0.84 0.89	NSE Daily: NSE Monthly:	0.85 0.96
5	Nong Khai/Vientiane (Thailand/Lao PDR)	NSE Daily: NSE Monthly:	0.93 0.95	NSE Daily: NSE Monthly:	0.84 0.89	NSE Daily: NSE Monthly:	0.86 0.95
6	Nakhon Phanom/Thakhek (Thailand/Lao PDR)	NSE Daily: NSE Monthly:	0.95 0.97	NSE Daily: NSE Monthly:	0.89 0.91	NSE Daily: NSE Monthly:	0.91 0.93
7	Mukdahan/Savannakhet (Thailand/Lao PDR)	NSE Daily: NSE Monthly:	0.94 0.96	NSE Daily: NSE Monthly:	0.90 0.91	NSE Daily: NSE Monthly:	0.93 0.95
8	Pakse (Lao PDR)	NSE Daily: NSE Monthly:	0.96 0.97	NSE Daily: NSE Monthly:	0.91 0.94	NSE Daily: NSE Monthly:	0.96 0.97
9	Stung Treng (Cambodia)	NSE Daily: NSE Monthly:	0.93 0.95	NSE Daily: NSE Monthly:	0.90 0.93	NSE Daily: NSE Monthly:	0.94 0.96

Model performance		THREW		SWAT		Source	
Performance for validation		**Period: 1985–1999**		**Period: 2009–2020**		**Period: 2010–2020 (only statistic, no validation)**	
1	Jinghong (China)	NSE Daily: NSE Monthly:	0.83 0.90	NSE Daily: NSE Monthly:	– –	NSE Daily: NSE Monthly:	– –
2	Chiang Saen (Thailand)	NSE Daily: NSE Monthly:	0.87 0.92	NSE Daily: NSE Monthly:	-0.81 -0.88	NSE Daily: NSE Monthly:	-0.01 0.07
3	Luang Prabang (Lao PDR)	NSE Daily: NSE Monthly:	0.86 0.91	NSE Daily: NSE Monthly:	0.08 0.90	NSE Daily: NSE Monthly:	0.50 0.61
4	Chiang Khan (Thailand)	NSE Daily: NSE Monthly:	0.87 0.90	NSE Daily: NSE Monthly:	0.50 0.53	NSE Daily: NSE Monthly:	0.65 0.79
5	Nong Khai/Vientiane (Thailand/Lao PDR)	NSE Daily: NSE Monthly:	0.86 0.89	NSE Daily: NSE Monthly:	0.39 0.40	NSE Daily: NSE Monthly:	0.62 0.73
6	Nakhon Phanom/Thakhek (Thailand/Lao PDR)	NSE Daily: NSE Monthly:	0.77 0.78	NSE Daily: NSE Monthly:	0.77 0.78	NSE Daily: NSE Monthly:	0.89 0.93
7	Mukdahan/Savannakhet (Thailand/Lao PDR)	NSE Daily: NSE Monthly:	0.86 0.88	NSE Daily: NSE Monthly:	0.75 0.78	NSE Daily: NSE Monthly:	0.89 0.92
8	Pakse (Lao PDR)	NSE Daily: NSE Monthly:	0.92 0.95	NSE Daily: NSE Monthly:	0.80 0.83	NSE Daily: NSE Monthly:	0.90 0.93
9	Stung Treng (Cambodia)	NSE Daily: NSE Monthly:	0.90 0.93	NSE Daily: NSE Monthly:	0.80 0.83	NSE Daily: NSE Monthly:	0.87 0.89

Note: The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ('noise') compared to the measured data variance ('information') (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE ranges from minus infinity to 1. Essentially, the closer to 1, the more accurate the model is. More specifically, (1) NSE = 1, corresponds to a perfect match of modelled to the observed data; (2) NSE = 0, indicates that the model predictions are as accurate as the mean of the observed data; and (3) minus infinity < NSE < 0, indicates that the observed mean is better predictor than the model.

2.3.5 Tools for the drought study

The Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI)

The SPI and SPEI are two meteorological drought indices. SPI was introduced in 1993 as a computed drought index based on precipitation records (Mckee et al., 1993). In addition, SPI has become a commonly used indicator for drought diagnosis worldwide (Guo et al., 2017; Liu et al., 2016; Song et al., 2021; Wang et al., 2021). The World Meteorological Organization (WMO) recommends the SPI as a reference drought index (Guo et al., 2017; Hao & AghaKouchak, 2014).

Vicente-Serrano et al. (2010) proposed SPEI to account for the impact of temperature on drought. SPEI is based on both precipitation and temperature. It has the advantage of combining multi-scale characteristics with the capacity to include the effects of temperature variability on drought assessments. As with the SPI, the SPEI has been widely used in drought assessment and is considered to be a reliable index for regional drought monitoring and analysis under global climate change(Li et al., 2021; Liu et al., 2016; Tirivarombo et al., 2018; Wang et al., 2021). This study uses both the SPI and SPEI for the meteorological drought analyses.

The method to determine the SPI and SPEI is elaborated in more detail in Annex G – Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI).

The Standardised Runoff Index (SRI)

Hydrological drought is a complex phenomenon and is usually defined as a period during which streamflow cannot meet the water supply demand under a given water management plan (Linsley Jr et al., 1975). Hence, a comprehensive hydrological drought assessment requires enormous effort and time to investigate and experiment with several drought indicators[9] (single-factor or multi-factor) and the applicability of these indicators in the regions and time scales. This study assessed the hydrological drought from a single-factor indicator, the Standardised Runoff Index (SRI).

The SRI is a widely used index to evaluate hydrological drought because of its straightforward calculation and simple requirement of input data (Madadgar & Moradkhani, 2014). The runoff inputs are the results of the Variable Infiltration Capability (VIC) model, a macroscale semi-distributed hydrologic model that solves water and energy balances, initially developed by the University of Washington (Liang et al., 1994). The VIC model has since been used extensively for basin- to global-scale applications that include hydrologic dataset construction, trend analysis of hydrologic fluxes and states, data evaluation and assimilation, forecasting, coupled climate modelling, and climate change impact assessment. Ongoing operational applications of the VIC model include the University of Washington's drought monitoring and forecasting systems and NASA's Land Data Assimilation System (Hamman et al., 2018).

The VIC model takes the input of precipitation from CHIRPS and temperature and wind from National Centres for Environmental Prediction (NCEP) to simulate daily runoff of 5 km resolution for the period of 1981–2020. Then, the SRI is calculated from the runoff for an annual time scale.

[9] Single-factor indicators include the Standardized Water Level Index (SWI)–based on groundwater levels, Standardized Streamflow Index (SSI)–based on streamflow, Standardized Runoff Index (SRI)–based on runoff, etc. Multi-factors indicators are the Surface Water Supply Index (SWSI)–required reservoir storage, runoff, precipitation, and snow accumulation and the Palmer hydrological drought index (PHDI)–considered precipitation, evapotranspiration, runoff, and soil moisture, and other factors.

The Mann-Kendall trend test

The Mann-Kendall (MK) test is a non-dimensional statistical method used to detect trends in time series (Kendall & Gibbons, 1990; Mann, 1945), and is recommended by the World Meteorological Organization (WMO) for trend analysis (Liu et al., 2016). The Mann-Kendall test expresses the trends in a slope over 100 years, where negative slopes (expressed in red tones) represent worsening drought conditions, and positive slopes (expressed in blue tones) represent improving drought conditions. The Mann-Kendall test was employed to examine the temporal trends in the trend of SPI and SPEI for this study. For all results, the significance of the trend was tested at the 5% level.

3 ANALYSIS AND DISCUSSIONS

3.1 Basin-wide development

3.1.1 Land cover/use changes

The land cover dataset for 1982–2015 from the Earth Science Center, Tsinghua University (Liu et al., 2020) reveals changes in the land cover over the LMRB, as indicated in **Figure 7**. The 1982–2015 period is divided into three time periods: 1982–1993, 1993–2004, and 2004–2015, with bluer colours indicating the recovery of vegetation and redder colours indicating deforestation. From 1982 to 1993, the Lancang River basin is significantly redder than during the last two time periods. The Mekong River basin has a less red area. In 1993–2004 and 2004–2015, the blue area in the Lancang River basin increased, and the red area decreased, indicating that large areas of farmland and grassland were converted to forest. This is due to the promotion of soil and water conservation project in China. The red area in the lower reaches of the Mekong River basin increased significantly, indicating considerable deforestation.

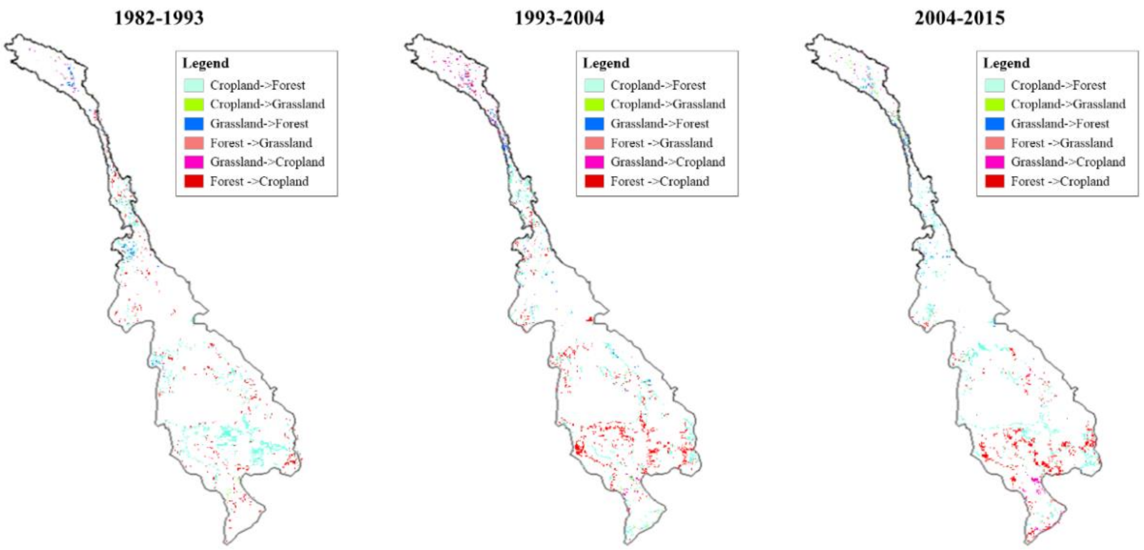

Figure 7. Change of land cover/use in the LMRB in 1982–1993, 1993–2004 and 2004–2015

MRC studies on land cover/use change detection for the Mekong River Basin from 2003 to 2020 shows that the quality/type of the forest changes between deciduous and evergreen and an increment of annual crop about 2–8% (Kityuttachai et al., 2016; MRC, 2019).

In 2003, the largest area of the Mekong River basin was a broadleaved evergreen forest (30%). In 2010, broadleaved deciduous forest (29%) and paddy rice (22%) covered most of the total area. These types represent the influence of a combination of natural resources and development (MRC, 2019).

Between 2003 and 2010, the land cover types that increased the most in the area across the Mekong River Basin 2003 and 2010 were shrubland (+8%), broadleaved deciduous forest (+8%), industrial plantation (+3%), annual crop (+2%) and orchard (+1%). Those that decreased were broadleaved evergreen forest (-20%), paddy rice (-2%), and grassland (-1%). Monitoring land cover change is an indirect indicator of basin development - providing insight into the basin's landscape dynamics.

3.1.2 Basin-wide water resource development

Since the 1950s, Southeast Asia has seen rapid economic development. This has been underpinned by reservoir construction for both irrigation and hydropower purposes. The pace of **hydropower** development varies from country to country based on national and regional economic and social development requirements. The construction of reservoirs in Thailand is mainly for irrigation. In Lao PDR, central Viet Nam and China, storage has been developed mainly to support reliable power generation. Reservoir development in Myanmar is mostly at the planning stage, while fewer large reservoirs have been developed in Cambodia due to the flat topography. The updated MRC hydropower database shows a sharp increase in the number of hydropower projects completed from 2009. As indicated in **Figure 8**, total basin storage has gradually increased over the last 10 years from some 20 to 100 billion m^3, which ranges from 5% of total Mean Annual Runoff (MAR) at Stung Treng for 2000–2009 (444 billion m^3) and 27% of MAR for 2010–2020 (366 billion m^3). Most of these projects are found in Lao PDR (**Figure 10**). However, despite the significant number of hydropower developed over the period from 2010 to 2020, about 40% of the active storage was already in place in 2010.

The MRC Council Study reveals that **irrigation** is the most prominent consumptive water use[10] in the Mekong River Basin. The updated MRC Irrigation Database includes 6,755 irrigation projects with 4.8 million ha of actual irrigable area. There are 6,596 existing irrigation headworks with an irrigated area in the wet season of 4 million ha. The 1,317 irrigation reservoirs have total active storage of about 17 billion m^3 and an active capacity for irrigation of 11 billion m^3. The irrigated area within the basin is estimated to be 10% in Cambodia, 5% in Lao PDR, 17% in Thailand, and 68% in Viet Nam.

Another dataset from FAO suggested the total water withdrawal in the LMRB in 2011 was 62 billion m^3, or 13% of the river's average annual discharge and irrigation withdrawal accounts for 56 billion m^3, or 91% of the total (FAO, 2012). Total water withdrawal in the Lancang River basin was 2.8 billion m^3 in 2020, and 2.2 billion m^3 was used by the agricultural sector (CJW, 2020). Though a large consumptive amount of water, due to gradual changing, irrigation is not expected to contribute largely to the hydrological changes between the two periods. However, there may be some reduction of flows due to upstream irrigation in the dry season.

The total population in the Mekong River Basin in 2007 was about 63 million, with approximately 50% living in Thailand and 28% in Viet Nam. Cambodia and Lao PDR accounted for 13% and 9% of the basin population, respectively. The basin's total **domestic water** demand was estimated at around 2 billion m^3 per year in 2007. This was expected to increase by 27% by 2020. Recent records suggest that large increases in water demand were noticeable in each country in 2020. Domestic water demand in Viet Nam had the highest growth by 83%, followed by Lao PDR (64%) and Cambodia (45%). These larger-than-expected increases reflect both increasing populations and growing wealth. Total domestic demands in the LMB are, however, less than 1% of the total runoff in estimate, and could potentially be discounted for this assessment.

Data and information on **industrial water use** in the basin are limited. The total industrial water demand was estimated to be approximately 232 million m^3 in 2007. This was expected to increase steadily by 171% by 2020. The highest growth in industrial demand is expected in Viet Nam (49%), followed by Thailand (40%). However, once again, these increases in water demands are a fraction of the total flows and can potentially be discounted for the purposes of this study.

[10] Water demand by hydropower is considered as non-consumptive use.

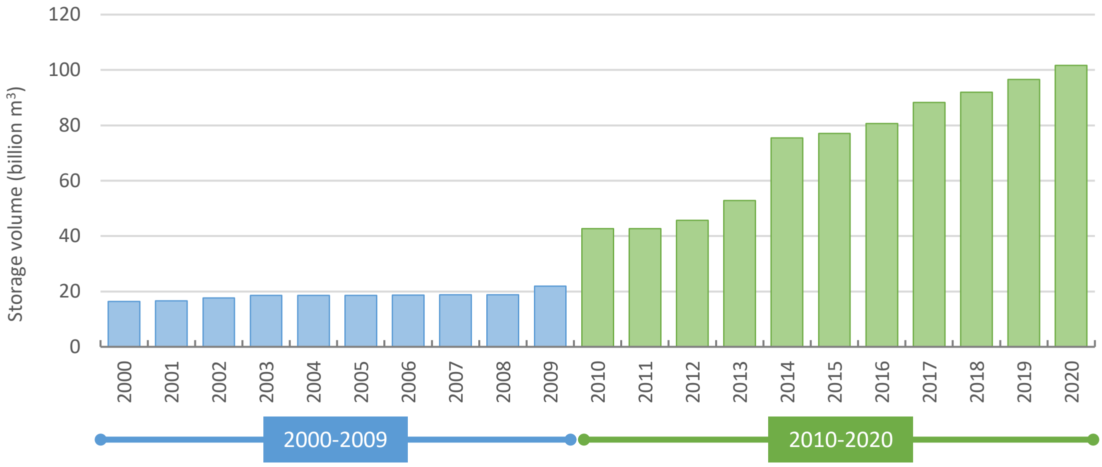

Figure 8. Cumulative storage capacity of hydropower on the mainstream and tributaries of the Lancang-Mekong River Basin

3.2 Climate change

A variety of trends have been examined to understand the extent of climate change already occurring within the Mekong River Basin. Tropical storms show neither an increasing nor decreasing trend and are likely to remain constant. However, with rising sea levels, the impact of storms might be greater, with greater damage. The temperature gradually increases by about 0.2°C per decade following the global trend. Whilst the number of cold days is expected to decrease, the number of hot days in a year exhibits no clear pattern as yet (MRC, 2019). The IPCC 6 report states that *there is high confidence that compound effects of climate change, land subsidence, and human factors will lead to higher flood levels and prolonged inundation in the Mekong Delta* (IPCC WG1, 2021).

Clear evidence for changes in precipitation patterns has also not been found. However, a slight increase in annual precipitation might happen after 2050. The extent and severity of flooding remain a critical component and need to be monitored carefully. In the future, basin-wide assessments of climate impact on flood behaviour suggest that flooded areas might increase by 2060 for floods of all return intervals by between 5% and 27%. The extent and severity of annual and wet season drought show a more favourable trend, suggesting that drought conditions seem to be reduced slightly due to an increase in annual and wet season precipitation, but the dry season drought is projected to be intensified in the future due to rising temperature and changes in rainfall patterns as indicated in **Figure 9** (Dong et al., 2022; MRC, 2019).

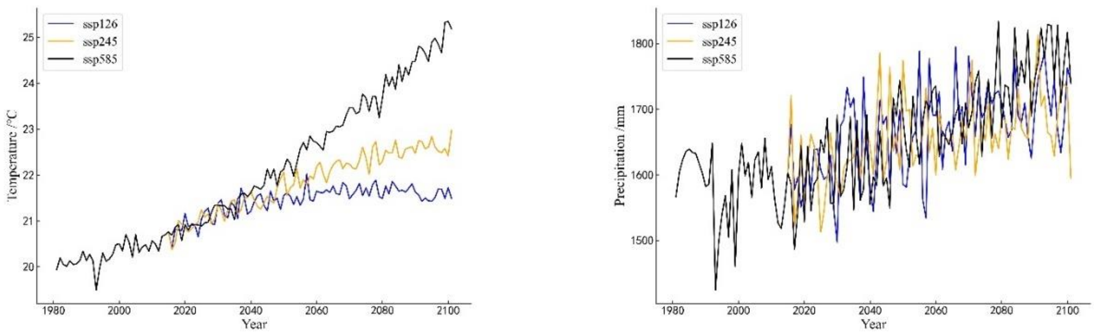

Figure 9. Future annual mean temperature (left) and precipitation (right) of LMRB (Dong et al., 2022)

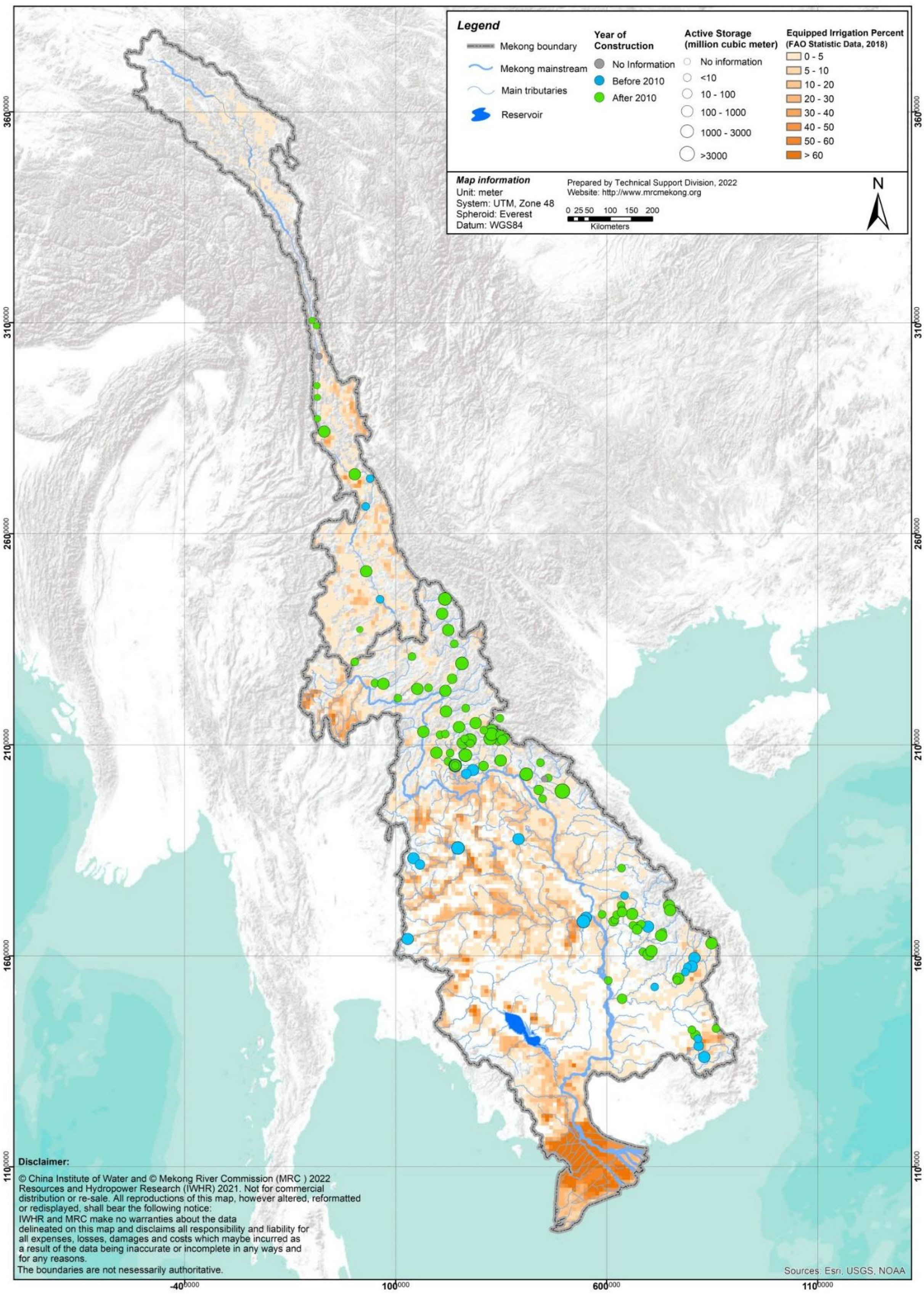

Figure 10. Hydropower and irrigation areas in the Lancang-Mekong River Basin

3.3 Changes in the spatio-temporal distribution of streamflow

3.3.1 Trends in average streamflow

Figure 11 shows monthly average flows at mainstream gauging from Jinghong to Stung Treng and rainfall in the area between stations. Daily analyses for both discharge and water level are provided as support materials in Annex H – Daily hydrographs 2000-2009 and 2010-2020.

One important observation is the reduction in annual and wet season flows in the 2010–2020 period is evident at all the sites (as compared to that in the 2000–2009 period). This marked flow reduction is seen in all key stations along the Mekong mainstream, as illustrated in **Figure 11**. A relatively dry climate could largely cause this in 2010–2020 (especially 2019–2020[11]) and other factors of irrigation water withdrawal in the wet season and reservoir regulation, which intercepts part of the flood water and releases the corresponding storage in the dry season.

Contrary to the wet season flow trends, the dry season flow for 2010–2020 is higher than for 2000–2009. This trend is also more notable at Chain Saen, Luang Prabang, and Chiang Khan, for reservoir regulation, as described in the previous paragraph.

Another important observation is the seasonality of the runoff of the Lancang-Mekong River is obvious: the flow in the wet season (June to November) can be 5 to 10 times that of the dry season (December to May). The streamflow seasonality in 2010–2020 changes as expected: in the wet season, the streamflow decreases, while in the dry season, the streamflow increases. The change of seasonality decreases at the stations downstream of Chiang Saen.

It is crucial to understand that the rise in water level in the dry season along the Mekong mainstream does not necessarily indicate a corresponding increase in water level (in the dry season) at Phnom Penh Port (on the confluence of the Tonle Sap River and Mekong River) and at Kampong Luong (on the Tonle Sap Lake), as indicated in **Figure 12**. This disparity is primarily attributed to the insufficient water level deviation necessary to induce a reverse flow towards the Tonle Sap Lake. In other words, despite increasing dry season water level on the Mekong mainstream, the conditions required to drive return water flow (in the opposite direction) to the Tonle Sap Lake may not be met.

The observed flows along the Lancang-Mekong mainstream over the last two decades therefore follow the accepted logic: Less rainfall results in low water level along the LMR mainstream in 2010–2020. During the wet season, some of the inflows to the storage reservoirs is retained to provide for hydropower generation or irrigation during the dry season. This reduces wet season flows and increases dry season flows. These changes are more prevalent where the storage makes up a greater proportion of the natural flows.

[11] Some care needs to be taken when directly comparing the two periods. As is demonstrated in the analysis of the drought section, 2019 and 2020 were exceptionally dry years. This reduces the average flow conditions for 2010-2020. Thus, the differences cannot be ascribed to the impacts of storage alone.

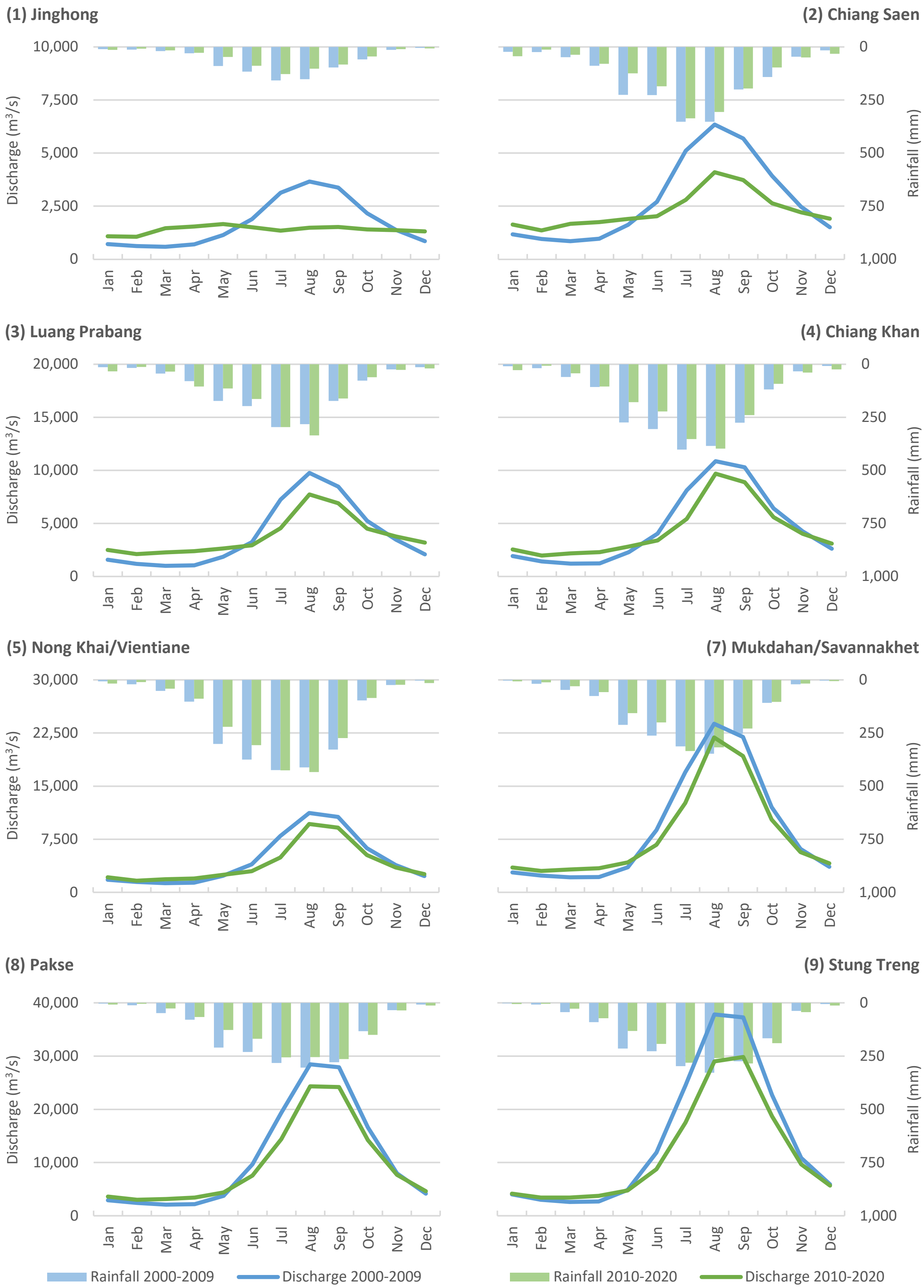

Figure 11. Monthly observed hydrograph for the key stations on the mainstream and areal observed rainfall over catchment area between the key stations before the major hydrological changes 2000–2009 (blue) and after the major changes of 2010–2020 (green)

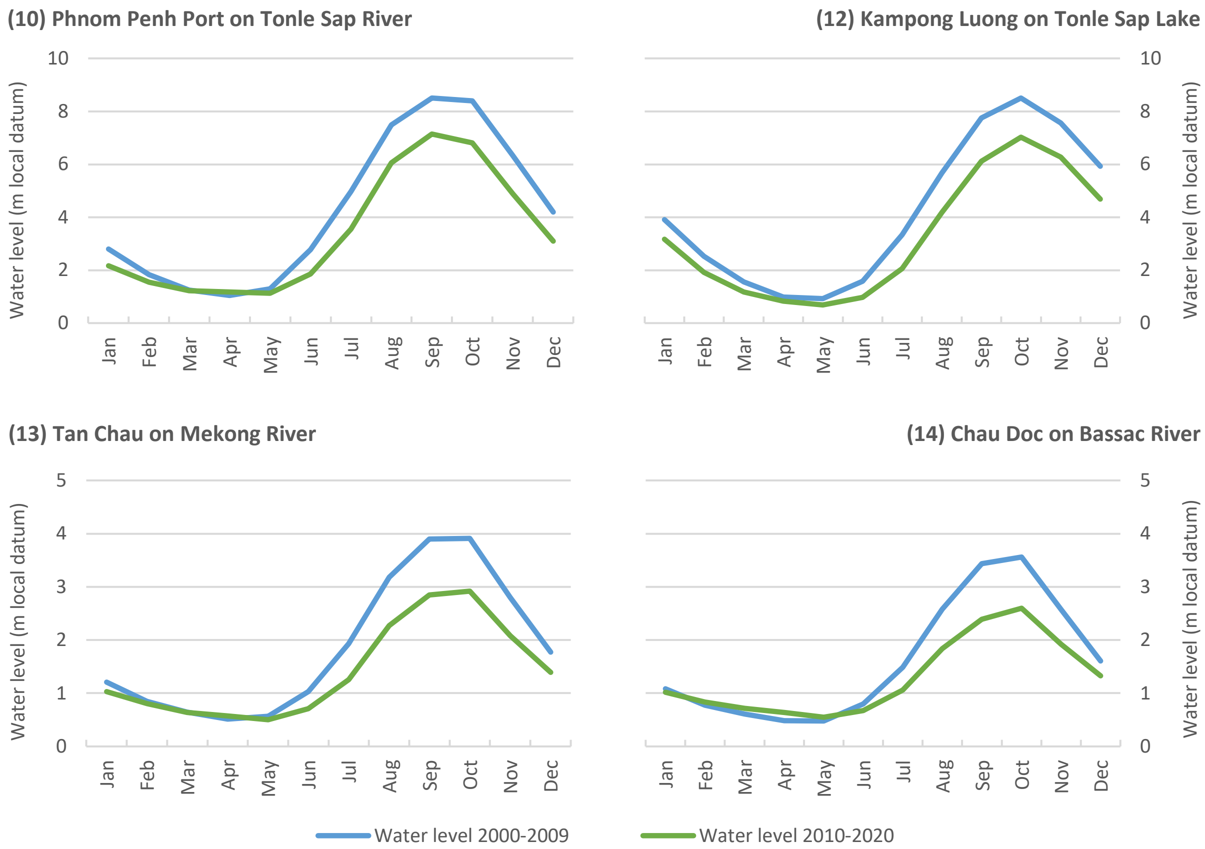

Figure 12. Monthly observed water level at Phnom Penh Port, Kampong Luong, Tan Chau and Chau Doc before and after the major hydrological changes 2000–2009 (blue) and after the major changes of 2010–2020 (green)

3.3.2 Trends in extreme streamflow

The magnitude of annual extreme flow conditions is presented by daily, weekly, monthly and 90-day maximum and minimum[12] streamflow along the LMR mainstream for the periods of 2000–2009 and 2010–2020, which are illustrated in **Figure 13** and **Figure 14**. The timing and duration of the annual extreme of daily minimum/maximum streamflow are depicted in **Figure 15**.

From upstream to downstream, the increases in dry season minimum streamflow become increasingly less noticeable than the decrease in wet season maximum flows. Compared to 2000–2009, the daily, weekly minimum, monthly and 90-day minimum flows for 2010–2020 at all mainstream hydrological stations are all higher, while the maximum flows are conversely lower. Overall, the drier climate is one of the main factors in the changes of flood peak flows in the wet season. Other key factors include irrigation withdrawal and reservoir regulations. However, the development of the basin has a greater relative impact on increasing extreme dry season flows than decreasing extreme wet season flows.

[12] The daily, weekly, monthly and 90-day minimum/maximum flows refer to the annual minimum/maximum values of the 1-day, 7-day, 30-day, 90-day average streamflow.

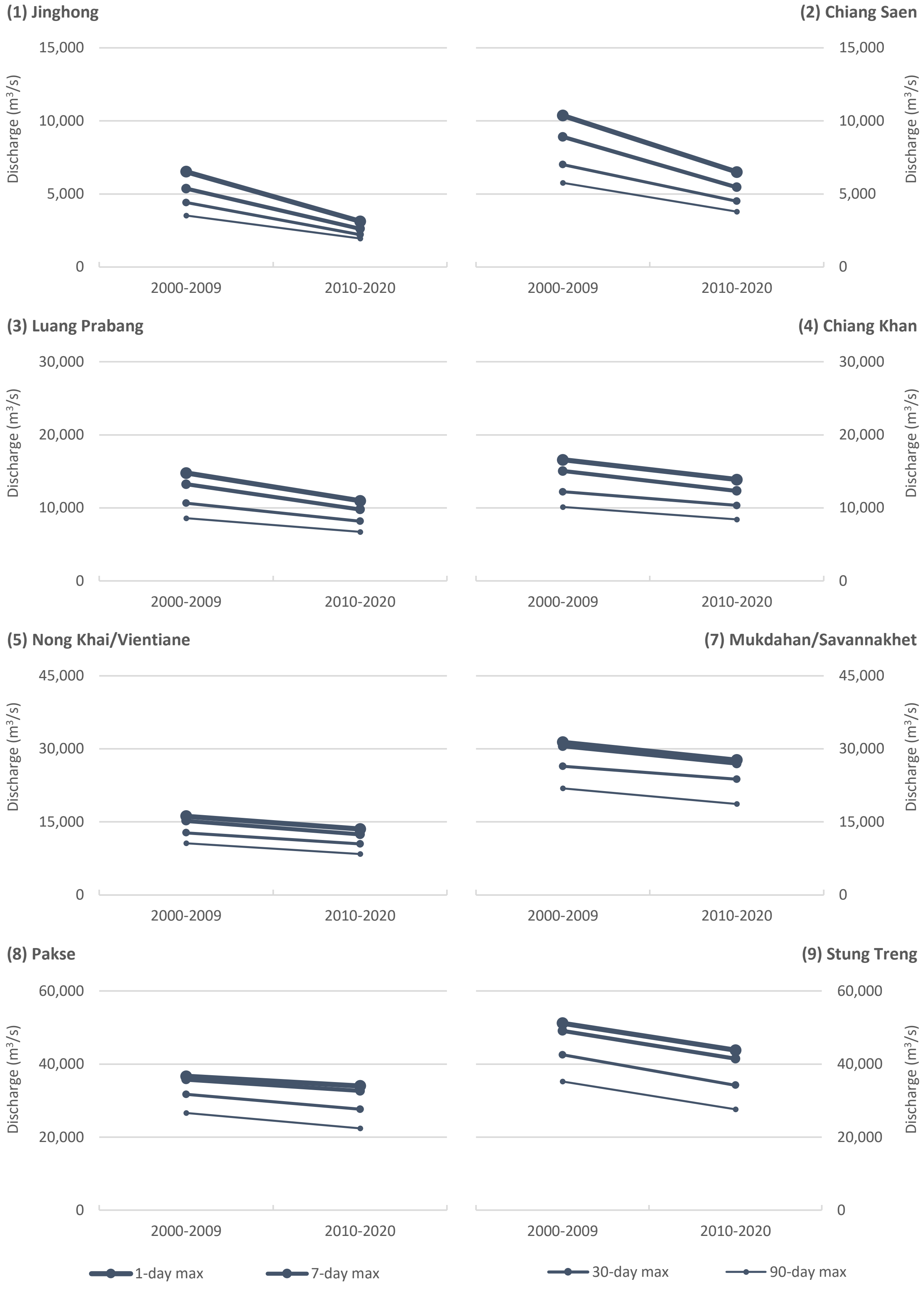

Figure 13. Daily, weekly, monthly, and 90-day maximum streamflow from Jinghong to Stung Treng for 2000–2009 and 2010–2020

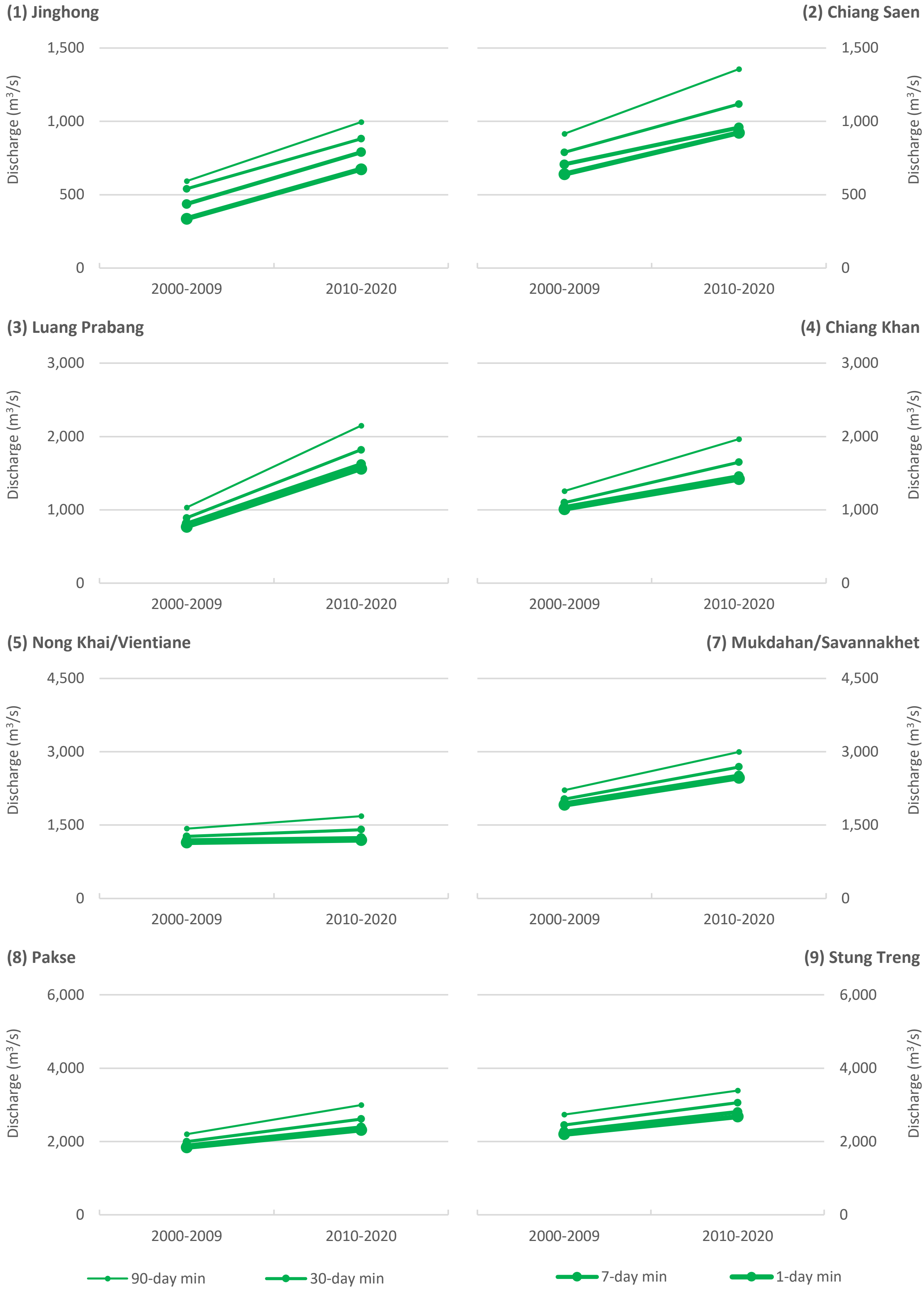

Figure 14. Daily, weekly, monthly, and 90-day minimum streamflow from Jinghong to Stung Treng for 2000–2009 and 2010–2020

The timing[13] of minimum daily flow usually starting in early April for the period of 2000–2009 shifts to mid-March for the period of 2010–2020, as shown in **Figure 15**. However, the average timing of maximum daily flows of the mainstream stations remains relatively the same, being late August or early September. This change suggests the duration between daily minimum and maximum tends to extend about three weeks (21 days) from 147 days (2000–2009) to 168 days (2010–2020) on average.

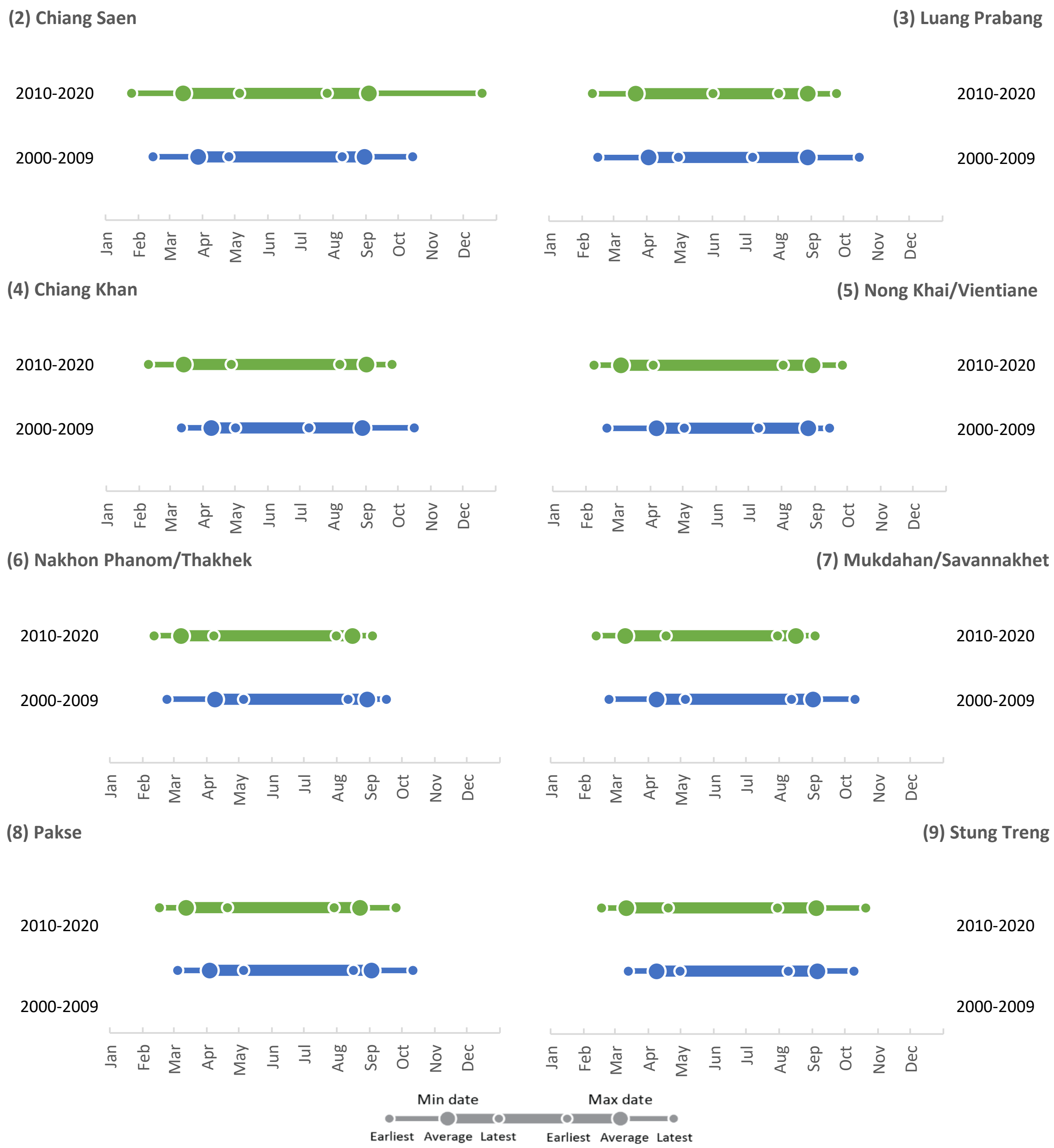

Figure 15. Timing of minimum/maximum streamflow and duration between the minimum and maximum of the annual extreme streamflow from Chiang Saen to Stung Treng for 2000–2009 (blue) and 2010–2020 (green)

13 Year 2019 was omitted from the analysis of the timing of 1-day minimum flow because the minimum discharge or water level occurred in November/December for most downstream stations of the Mekong River.

3.3.3 Seasonal distribution of streamflow

The seasonal pattern[14] of flows observed at different key stations for 2000–2009 and 2010–2020 is illustrated in **Figure 16** and **Figure 17**. Additional analysis on daily accumulated volume is presented in Annex I – Daily accumulated volume for 2000–2009 and 2010–2020.

Similar to the trends of observed streamflow for 2000–2009 and 2010–2020, the seasonal volume at all the mainstream stations is reduced for the wet season and increased for the dry season (**Figure 16** and **Figure 17**). As tabulated in **Table 5**, the increase in dry season volume between 2000–2009 and 2010–2020 was +76% at Jinghong, +44% at Chiang Saen, +20% at Nong Khai/Vientiane, +29% at Mukdahan/Savannakhet, and +9% at Stung Treng. The decrease in wet season volume is found to be -44% at Jinghong, -33% at Chiang Saen, -19% at Nong Khai/Vientiane, -15% at Mukdahan/Savannakhet, and -22% at Stung Treng.

Additionally, as the upstream stations with a low annual volume, Jinghong and Chiang Saen were the most affected stations, with a large shift of the seasonal volume (dry season volume over wet season volume): 20%/80% for 2000–2009 to 40%/60% for 2010–2020 (**Table 5**). This ratio became smaller for downstream stations, i.e., Chiang Khan to Nong Khai/Vientiane: 20%/80% for 2000–2009 to 30%/70% for 2010–2020 and Nakhon Phanom/Thakhek to Stung Treng: 15%/85% for 2000–2009 to 20%/80% for 2010–2020.

[14] The wet season runs from June to November, while the dry season is from December to May.

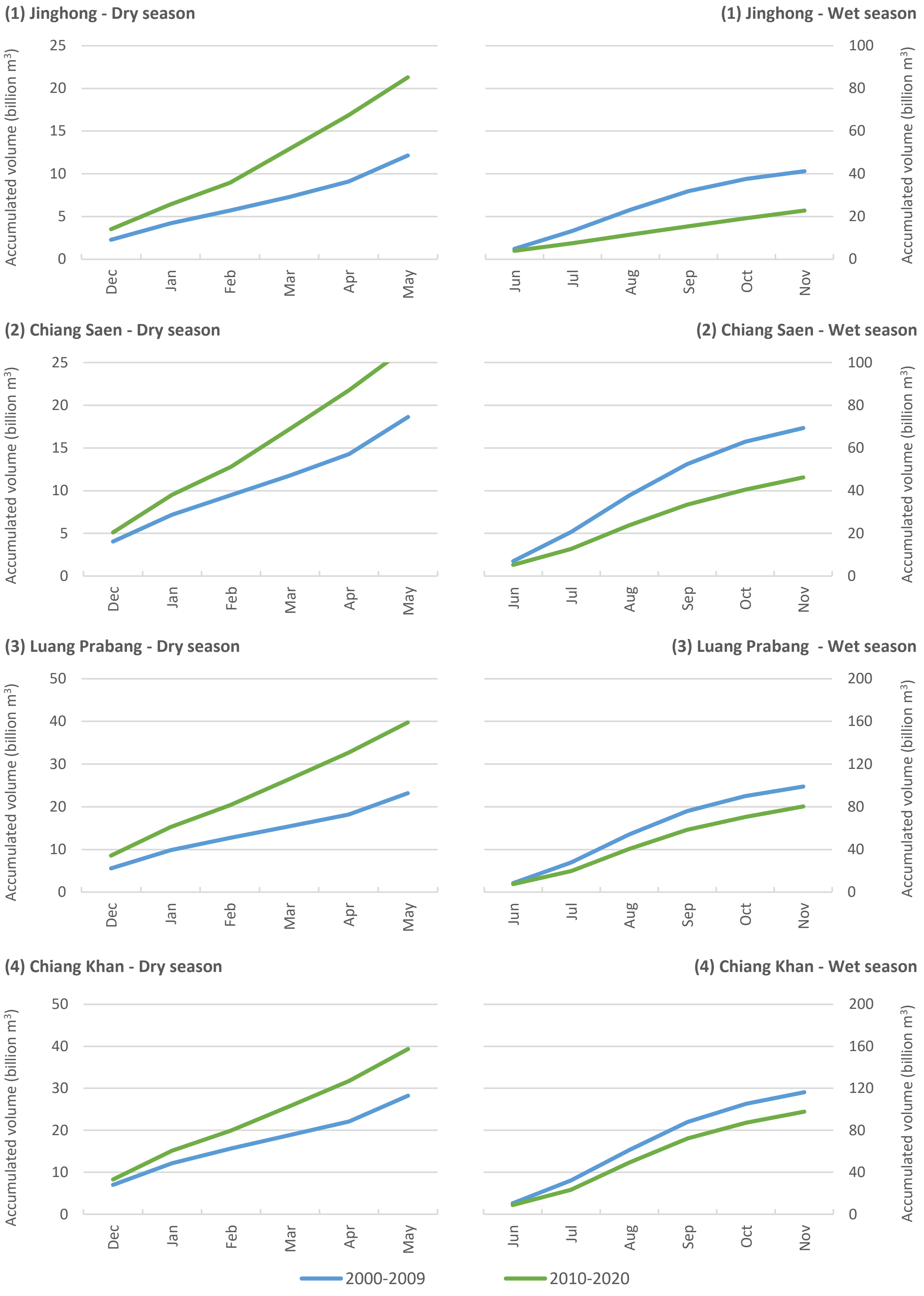

Figure 16. Accumulated volume from Jinghong to Chiang Khan for dry and wet seasons for 2000–2009 (blue) and 2010–2020 (green)

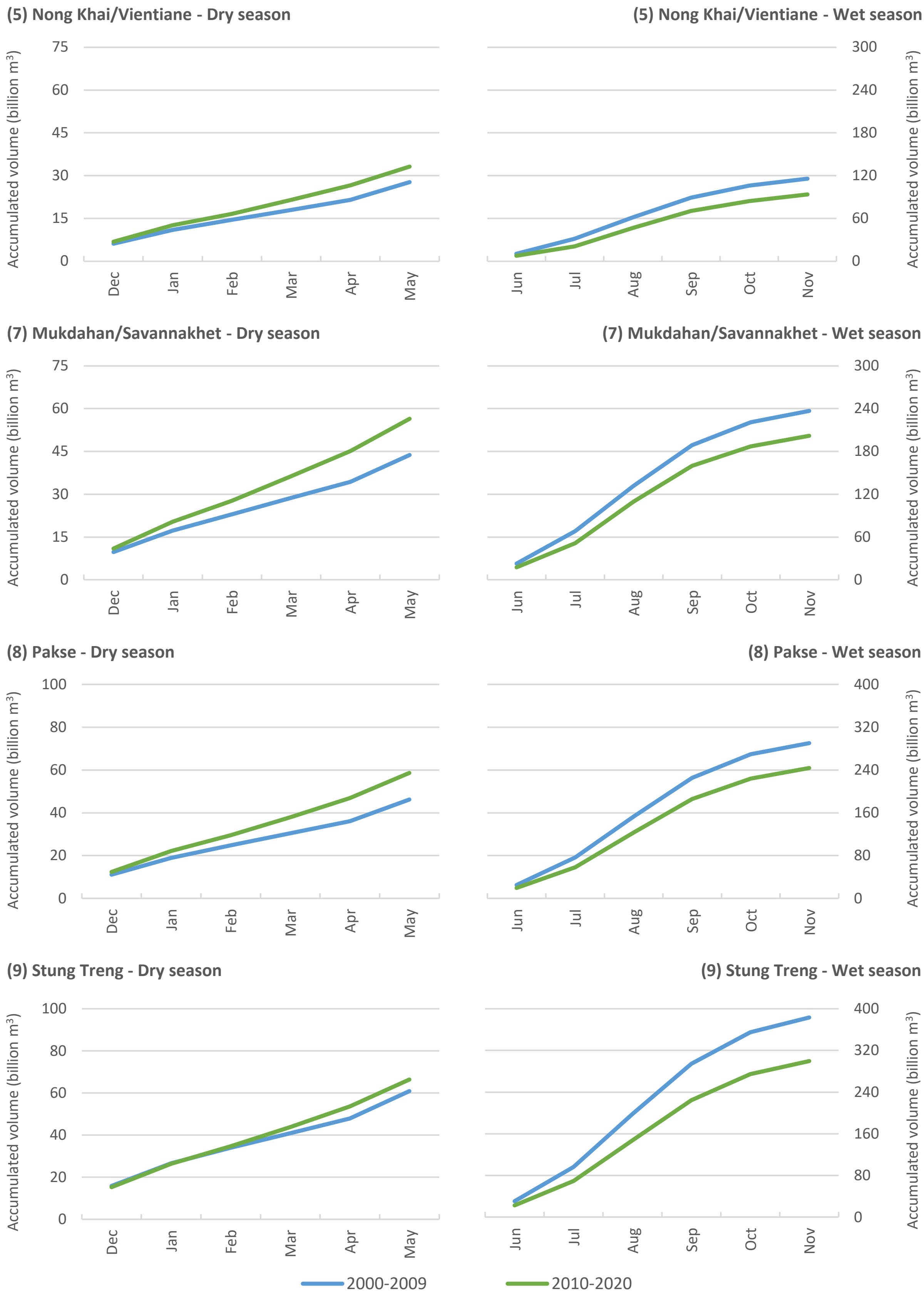

Figure 17. Accumulated volume from Nong Khai/Vientiane to Stung Treng for dry and wet seasons for 2000–2009 (blue) and 2010–2020 (green)

Furthermore, the total annual flow volume was estimated for both 2000–2009 and 2010–2020. As illustrated in **Figure 18**, the flow volume was evidently reduced for all stations along the Lancang-Mekong mainstream, varying between about -7 billion m^3 at Chiang Khan[15] and -78 billion m^3 at Stung Treng.

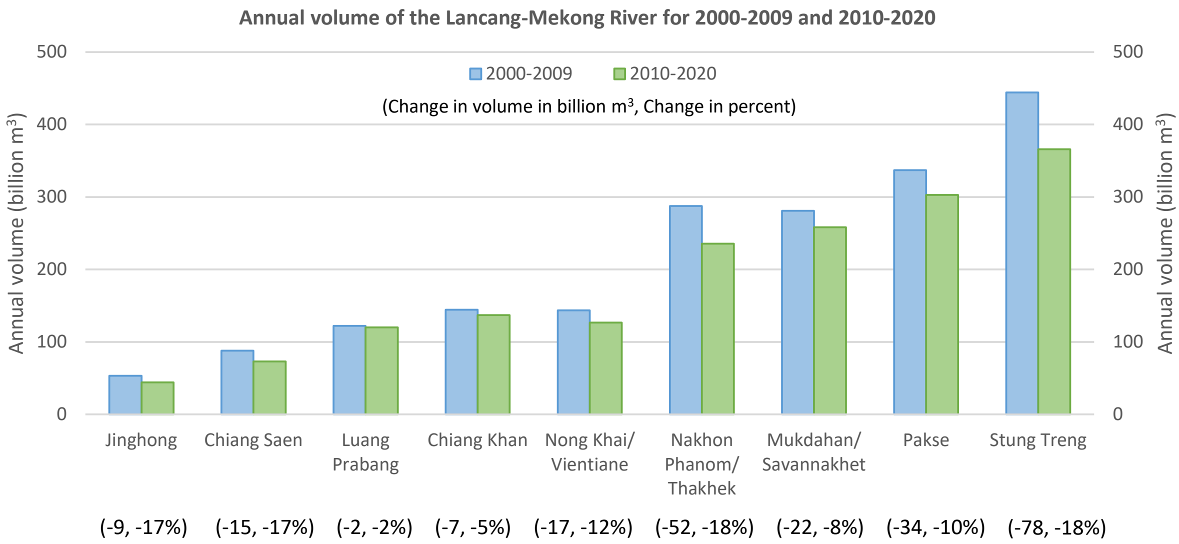

Figure 18. Changes in annual volume along the key stations of the Lancang-Mekong River for 2000–2009 and 2010–2020

The annual flow at Jinghong decreased by -9 billion m^3 or 17%. The reduction of the annual flow at Luang Prabang, Nong Khai/Vientiane and Stung Treng was -2 billion m^3 (-2%), -17 billion m^3 (-12%) and -78 billion m^3 (-18%), respectively. This supports the claims that the main cause of annual flow changes is the basin's heterogeneous and drier climate condition in 2019-2020.

15 Flow reduction at Luang Prabang was the lowest (-2 km^3) but believed to be higher as the station was under back-water effect of Xayabury dam, which became online in 2019. Hence, the estimate of flow at this station for post-storage period of 2010-2020 was impacted by this effect.

Table 5. Seasonal volume distribution for 2000–2009 and 2010–2020

(billion m^3)	Dry season		Wet season		Annual
Station	Volume	Ratio	Volume	Ratio	volume
(1) Jinghong (0 km)					
2000–2009	12	23%	41	77%	53
2010–2020	21	48%	23	52%	44
Deviation	+9	-	-18	-	-9
% change	+76%	+25%	-45%	-25%	-17%
(2) Chiang Saen (+343 km)					
2000–2009	19	21%	69	79%	88
2010–2020	27	37%	46	63%	73
Deviation	+8	-	-23	-	-15
% change	+44%	+16%	-33%	-16%	-17%
(3) Luang Prabang (+697 km)					
2000–2009	23	19%	99	81%	122
2010–2020	40	33%	80	67%	120
Deviation	+17	-	-19	-	-2
% change	+72%	+14%	-19%	-14%	-2%
(4) Chiang Khan (+992 km)					
2000–2009	28	20%	116	80%	144
2010–2020	39	29%	98	71%	137
Deviation	+11	-	-18	-	-7
% change	+39%	+9%	-16%	-9%	-5%
(5) Nong Khai/Vientiane (+1,158 km)					
2000–2009	28	19%	116	81%	144
2010–2020	33	26%	94	74%	127
Deviation	+5	-	-22	-	-17
% change	+20%	+7%	-19%	-7%	-12%
(6) Nakhon Phanom/Thakhek (+1,486 km)					
2000–2009	46	16%	242	84%	287
2010–2020	49	21%	187	79%	236
Deviation	+4	-	-55	-	-52
% change	+8%	+5%	-23%	-5%	-18%
(7) Mukdahan/Savannakhet (+1,579 km)					
2000–2009	44	16%	237	84%	281
2010–2020	56	22%	202	78%	258
Deviation	+13	-	-35	-	-22
% change	+29%	+6%	-15%	-6%	-8%
(8) Pakse (+1,841 km)					
2000–2009	46	14%	291	86%	337
2010–2020	59	19%	244	81%	303
Deviation	+12	-	-47	-	-34
% change	+27%	+6%	-16%	-6%	-10%
(9) Stung Treng (+2,024 km)					
2000–2009	61	14%	383	86%	444
2010–2020	66	18%	299	82%	366
Deviation	+5	-	-84	-	-78
% change	+9%	+4%	-22%	-4%	-18%

Note: It is important to note that the values don’t add to their sums or 100% because of rounding.
The dry season covers December to May from while the wet season is from June to November.

3.3.4 Hydrological flood patterns on the mainstream

The peak and flood volume hydrographs for the 2000–2009 and 2010–2020 periods at Chiang Saen, Chiang Khan, Vientiane/Nong Khai, Mukdahan/Savannakhet, Pakse, and Stung Treng are presented in **Figure 19**. In this section, a statistical analysis is undertaken to determine whether any extreme flood or hydrological drought events were evident over the full period. An analysis of the annual flood peak flow and annual flood volume[16] is used to provide an overview of the high and low flow characteristics of the Mekong mainstream in any one year, which is then set against 'typical years' using standard deviations.

This is done by comparing the standard deviations for the annual peak flow and annual flood volumes in any of the years. **Figure 19** shows the one (1β) and two (2β) standard deviations for the annual peak flow and annual flood volumes, with the standard deviation boxes. Events outside of the 1β box reflect 'significant' flood or drought years. Those outside of the 2β box could be defined as historically 'extreme' flood and drought years.

This analysis shows that 2019 and 2020 would be considered *extreme hydrological drought years* throughout the Lancang/Mekong mainstream, lying outside the 2β standard deviation at all the key flow gauging points (**Figure 19**). However, there are several years in 2010–2020 that *could* be considered *significant hydrological drought years* lying outside of the 1β standard deviation in the lower left quadrant. This is particularly true for the downstream stations. This is not as evident in 2000–2009. Here, several years lie outside the 1β standard deviation box, apparently due to *higher total flood volumes or severe flood years*, i.e., in the upper right quadrant of the standard deviation box. However, it is not possible to determine whether these effects are a result of the increased storage or are due to changing mereological conditions due to the limited length of the data period.

[16] Annual flood volume is calculated for the flood season (of a given year), which is defined as period of the year when flows are above their long term annual average.

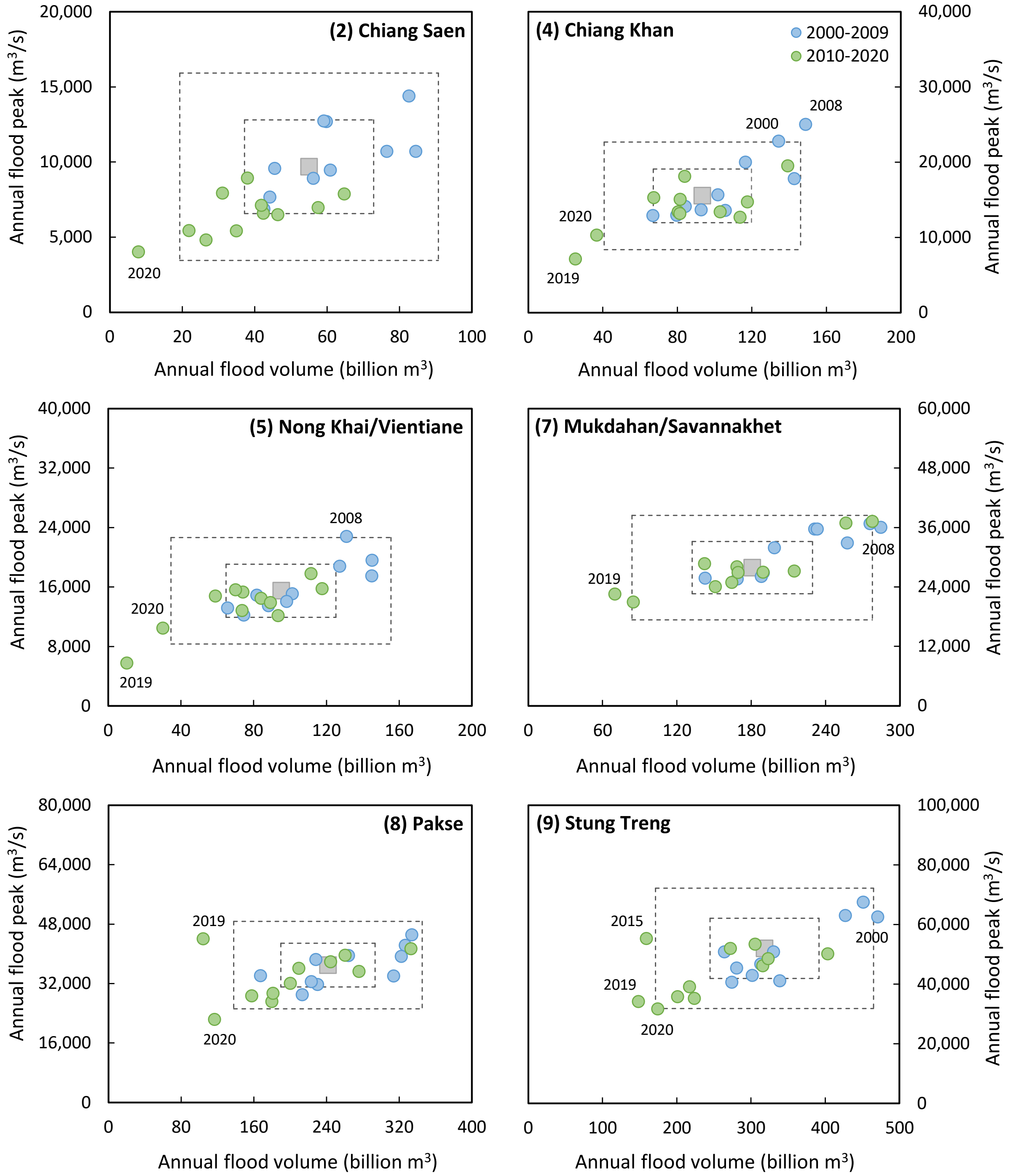

Figure 19. Distribution of annual flood peak and annual flood volume at the key hydrological stations along the Mekong mainstream. Blue points are the flood peak and flood volume for 2000–2009, while green points are the flood peak and flood volume for 2010–2020

3.4 Changes in the timing flood pulse of Tonle Sap Lake

The observed accumulated reverse flows to the Tonle Sap Lake during 2000–2009 and 2010–2020 are shown together with the minimum, maximum, and average monthly reverse flows in **Figure 20**. Daily accumulated reserve flows to the Lake are given in Annex J – Daily observed reverse flow to the Tonle Sap Lake for 2000–2009 and 2010–2020.

As already seen for the observed flow trends of mainstream stations, the accumulated flows during 2010–2020 are lower when compared to 2000–2009. One of the most striking observations is that the gap between the maximum and minimum return flow volumes for 2010–2020 has increased. This is particularly evident during the peak flow months (August to October). There is a difference of 34 billion m^3 of accumulated reverse flow between the minimum and maximum (in October) for 2010–2020, but it is only around 19 billion m^3 for the same months in 2000–2009.

Moreover, the average accumulated flow volume in October dropped by around 11 billion m^3 for 2010–2020. Notably, the difference between the minimum flows for the two periods is higher than that of maximum flows. This increased variability is a strong indicator that these differences have been driven, at least in part, by the drought conditions in the 2010–2020 period.

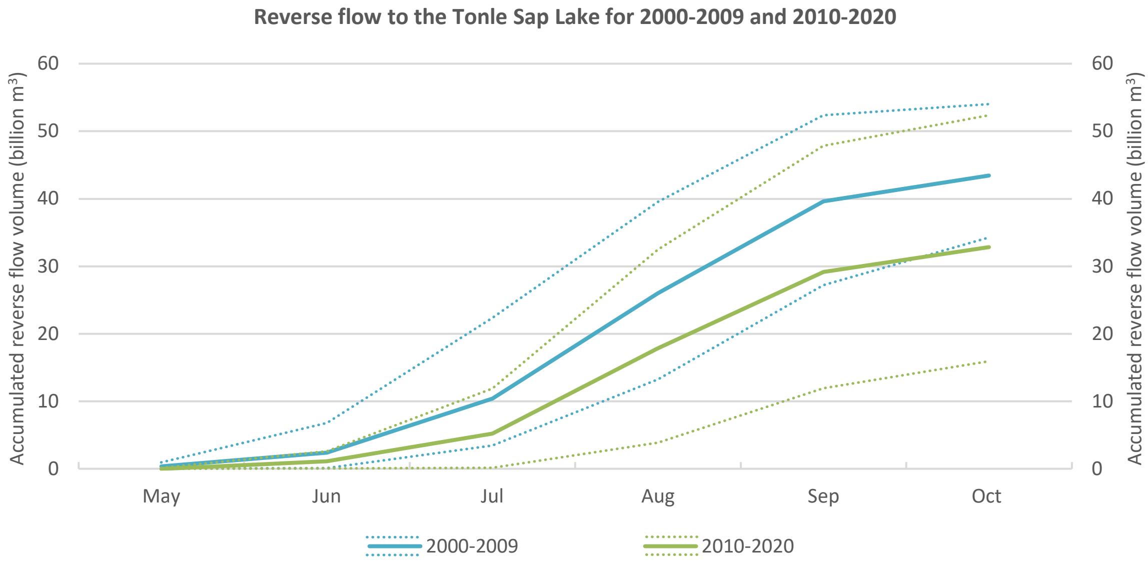

Figure 20. Observed (min-max-average lines) reverse flow to the Tonle Sap Lake for 2000–2009 (blue) and 2010–2020 (green)

Table 6 indicates that the Tonle Sap Lake experienced a large variation of hydrological conditions in the period of 2010–2020, as the most extreme situation in the 20-year records occurred in this period. The start and end dates extend to a full range of earliest to latest dates. The duration and volume of the reserve flow cover between the lowest and highest values.

A comparison between the two periods (**Figure 21**) reveals that the start date of the reverse flow began about three weeks late (a 19-day difference between 16 June and 28 May). However, the end of date of the reverse flow only slightly changed (4-day earlier, from 24 September to 28 September). This change suggests that the duration of the reverse flow for 2010–2020 (102 days) was 3-week shorter than that of 2000–2009 (124 days).

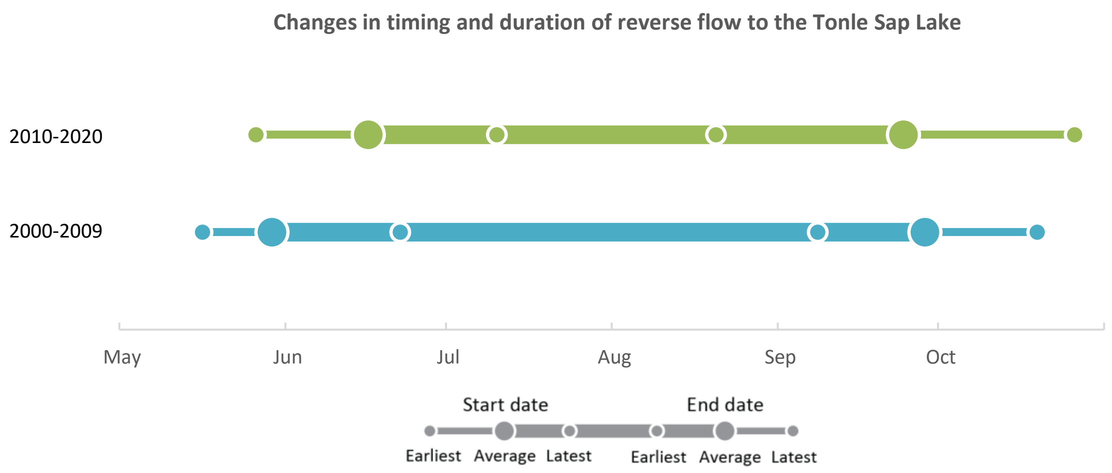

Figure 21. Timing and duration of reserve flow to the Tonle Sap Lake for 2000–2009 (blue) and 2010–2020 (green)

Table 6. Summary of accumulated reverse flows to the Tonle Sap Lake for 2000–2020

Year	Start date	End date	Duration (day)	Reverse flows (billion m^3)	Change (billion m^3/day)
2000	17 May	20 Sep	127	46.9	0.37
2001	29 May	21 Sep	116	49.8	0.43
2002	27 May	23 Sep	120	54.0	0.45
2003	01 Jun	01 Oct	123 [H*]	38.9	0.32
2004	02 Jun	27 Sep	118	44.6	0.38
2005	22 Jun	04 Oct	105	53.7	0.51
2006	03 Jun	08 Sep	98	39.3	0.40
2007	17 May	19 Oct [H*]	156	36.7	0.24 [L**]
2008	16 May [L***]	30 Sep	138 [H***]	35.5	0.26 [L*]
2009	26 May [L**]	10 Oct	138 [H***]	37.7	0.27
2000–2009					
Average	28 May	28 Sep	124	43.7	0.36
Min	16 May	08 Sep	98	35.5	0.24
Max	22 Jun	19 Oct	156	54.0	0.51
2010	10 Jul [H***]	23 Oct [H**]	106	29.4	0.28
2011	30 May	29 Sep	123 [H*]	52.4 [H***]	0.43 [H**]
2012	27 May	20 Sep	117	33.3	0.28
2013	17 Jun	04 Oct	110	38.3 [H*]	0.35
2014	14 Jun	07 Sep [L**]	86 [L**]	36.3	0.42 [H*]
2015	25 Jun [H*]	21 Sep	89	24.1 [L**]	0.27
2016	21 Jun	28 Sep	100	26.9 [L*]	0.27
2017	26 May [L*]	20 Aug [L***]	87 [L*]	27.3	0.31
2018	10 Jun	10 Sep [L*]	93	46.1 [H**]	0.50 [H***]
2019	06 Jul [H**]	27 Sep	84 [L***]	31.5	0.37
2020	25 Jun	26 Oct [H***]	124 [H**]	18.9 [L***]	0.15 [L***]
2010–2020					
Average	16 Jun	24 Sep	102	33.1	0.33
Min	26 May	20 Aug	84	18.9	0.15
Max	10 Jul	26 Oct	124	52.4	0.50

Note: [H***] is the first latest date or highest value; [H**] is the second latest date or highest value; [H*] is the third latest date or highest value for 2000–2020.

[L***] is the first earliest date or lowest value; [L**] is the second earliest date or lowest value; [L*] is the third earliest date or lowest value for 2000–2020.

3.5 Modelling results

The impacts of the storage on mainstream flows and water use were based on model simulations, specifically the THREW, SWAT, and Source models. The first step in this process was to validate the modelling results by comparing the generated discharge for the study period of 2000–2020 to the observed discharge. The performance of the three models discussed in this section by illustrating observed and simulated flows from the models for 2000–2009 and 2010–2020 periods at the key stations on the Lancang-Mekong mainstream. Once validated, the sensitivity of the models to changing climate inputs (rainfall, temperature, and evaporation) can be compared to changes due to the development of the storage (**Figure 22** and **Figure 23**).

The three models performed exceptionally well for 2000–2009 conditions, where the mainstream flows were more 'natural.' However, SWAT did not perform well in 2010 − 2020, where the natural flows were modified by the increasing storage volume, operations of the hydropower projects, and irrigation development (to a lesser extent) in the basin.

3.5.1 Simulated flows from the THREW model

For 2000–2009, the natural and observed regime curves are almost identical, which means the hydrological model performs well. The performance of the THREW model is 0.8 and above in both the calibration (2000–2009) and validation (1985–1999) periods at nine stations in the mainstream of the Lancang-Mekong River.

For 2010–2020, the observed streamflow is already influenced by the development (including reservoirs and withdraws), while the THREW model simulates streamflow without the influence of the development activities. The average monthly runoff is basically similar to the observed discharge, with less runoff in the dry season and more runoff in the wet season (when compared with the observed flow). At the upper hydrological stations (Jinghong and Chiang Saen), the model is not able to well capture the monthly hydrographs by overestimating and underestimating the runoff during the wet and dry seasons, respectively. The model can provide a satisfying agreement between simulated and observed discharges from the Luang Prabang to Pakse during the wet season. However, the model overestimates the runoff during wet seasons while generating an acceptable performance at Stung Treng station during the dry season. This indicates that in overall, the simulated streamflow of the THREW model well reproduced the monthly runoff during the wet season while underestimating the monthly natural runoff during the dry season in 2010–2020.

In short, the THREW model provides good results for the monthly runoff in both periods, which could help reconstruct the natural runoff and contribute to a separation of hydrological changes caused by the changing climate and human activities.

3.5.2 Simulated flows from the SWAT model

The calibrated SWAT model provides simulated discharge without considering the operations of the hydropower or water diversions for irrigation. The results are satisfactory for the 2000–2009 period. However, after 2010, the SWAT did not simulate daily and monthly flow as it could not accommodate hydropower operations and irrigation abstractions. Thus, there is a mismatch between the observed and simulated flows from SWAT after 2010 (**Figure 22** and **Figure 23**).

This is particularly evident in the Lancang section. In the Mekong section, the impacts on mainstream flows are influenced by the larger tributaries where a smaller proportion of the total runoff is regulated.

3.5.3 Simulated flows from the Source model

The Source water system model took inflows from the SWAT hydrological model and ran them through the basin's existing water infrastructure (storage, irrigation, and domestic/industrial water demands). The Source model was configurated to accommodate the commissioning dates for all the storage in the LMRB. Attempts to match the storage strategy of the two largest reservoirs on the Lancang - Nuozhadu and -Xiaowan were also made. The results from the Source modelling show significant improvement in the simulations at Chiang Saen for 2010–2020 (Figure 22) compared to the MRC Council Study. Thus, highlighting the importance of including reservoir-specific operations in the model simulations.

Further downstream, the observed discharges closely match the simulated discharges for most of the stations, except for Pakse and Stung Treng (Figure 23). The reasons for this are not immediately evident. However, the impacts of using a generalised rule curve to simulate hydropower operations will be increasingly evident.

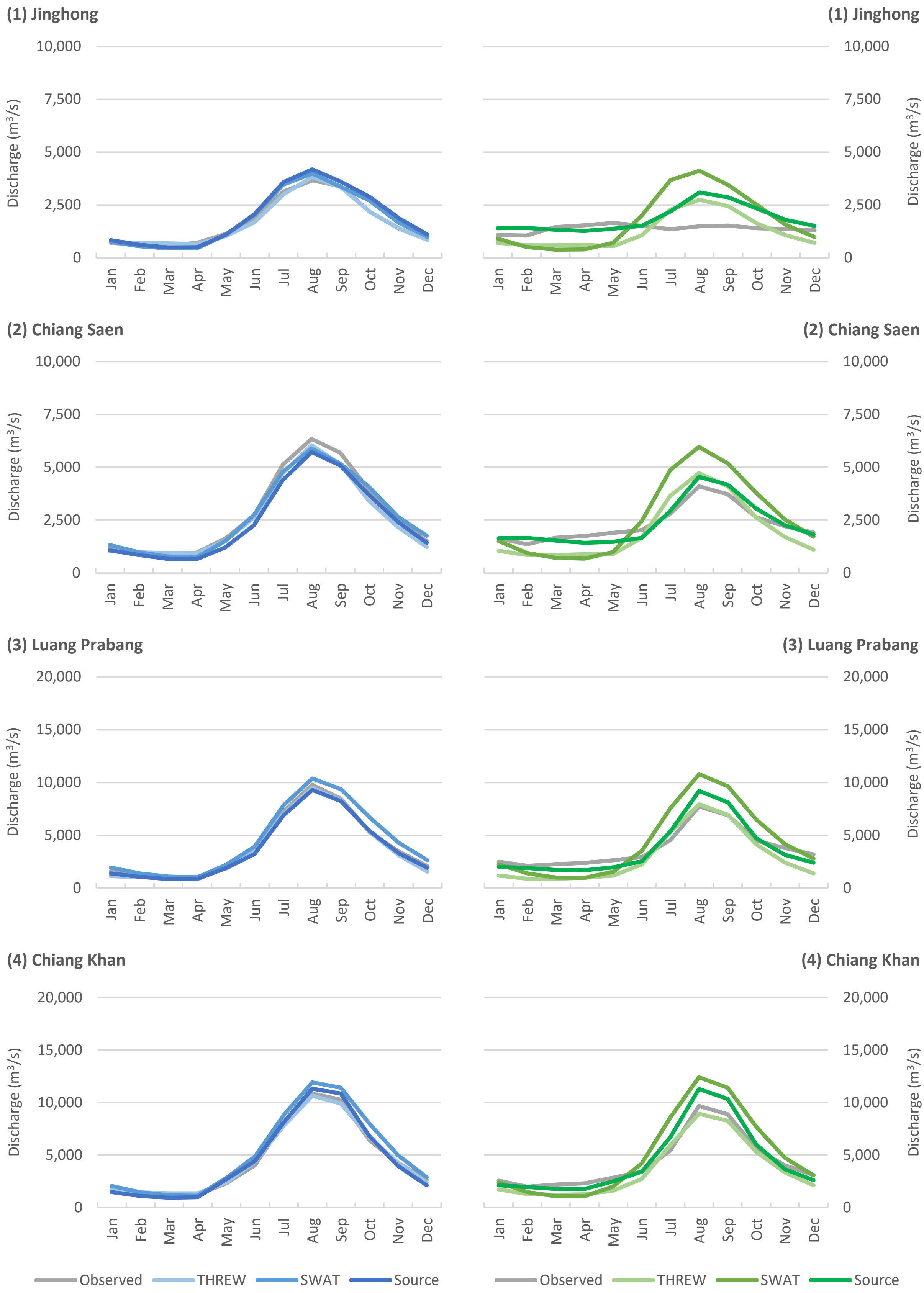

Figure 22. Monthly observed/simulated hydrograph from THREW, SWAT, and Source for stations from Jinghong to Chiang Khan for 2000–2009 (blue tone) and 2010–2020 (green tone) versus observed discharge (grey)

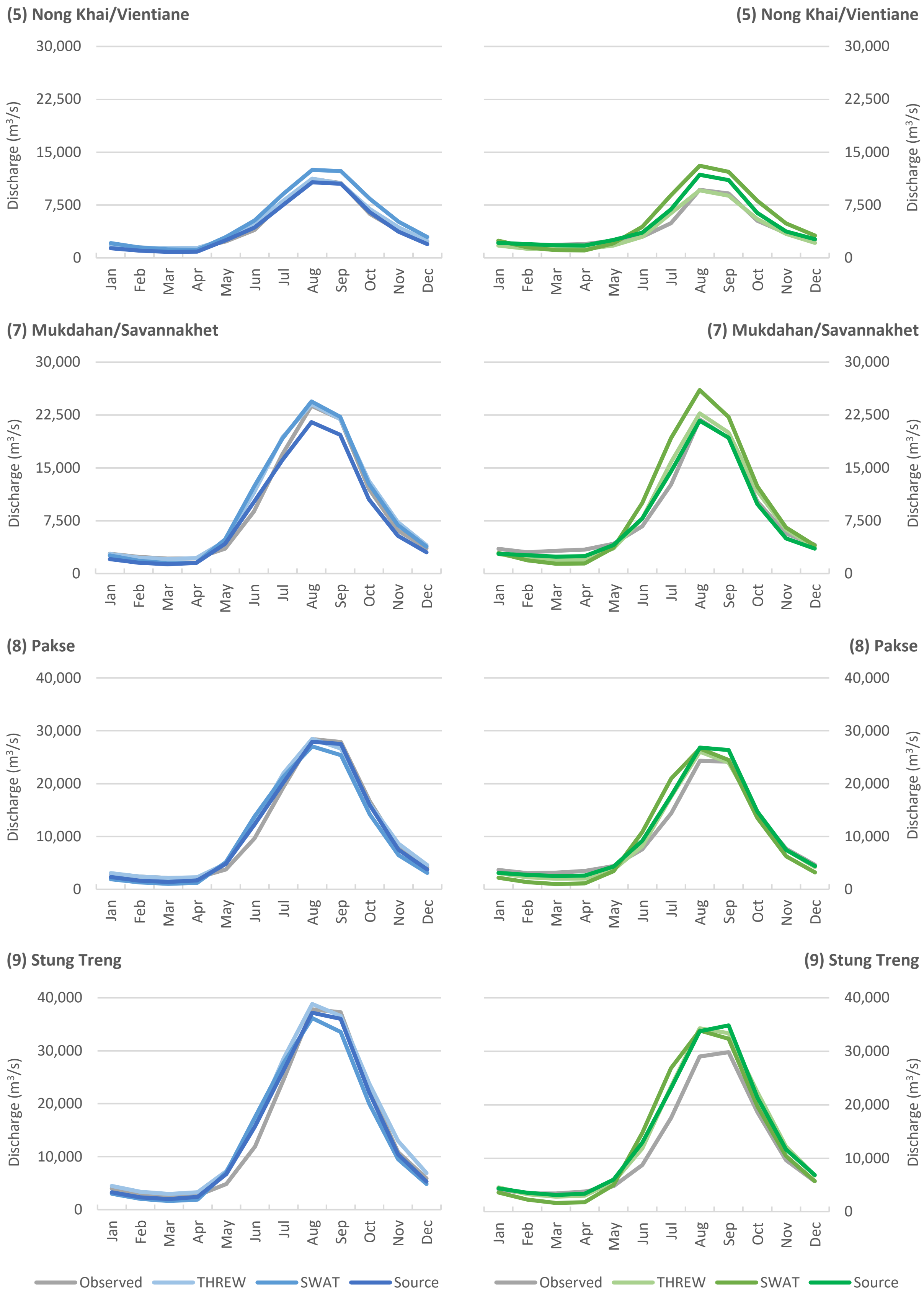

Figure 23. Monthly observed/simulated hydrograph from THREW, SWAT, and Source for stations from Nong Khai/Vientiane to Stung Treng for 2000–2009 (blue tone) and 2010–2020 (green tone) versus observed discharge (grey)

3.5.4 'Natural runoff' composition using the THREW model

'Natural runoff[17]' was simulated from 2000 to 2020 using the THREW model. This was used to calculate the relative contribution of flow in the Lancang River and the other 12 main tributaries to the Mekong mainstream. This was done for the 8 hydrological stations along the Mekong River. The results from the THREW model for the periods of 2000–2009 and 2010–2020 are listed in **Figure 24** and in **Table 7**.

Not surprisingly, the annual contribution ratio from Lancang River shows a decreasing trend with the increase in river distance. The annual ratio was 66.4% for the period 2000–2009 and 62.2% for the period 2010–2020 at Chiang Saen (343 km from Jinghong); 16.6% for the period 2000–2009 and 15.3% for the period 2010–2020 in Nakhon Phanom/Thakhek (1,486 km from Jinghong); and 10.1% for the period 2000–2009 and 9.2% for the period 2010–2020 in Stung Treng (2,024 km from Jinghong). At Stung Treng, the main tributaries contributed substantial water volume to the mainstream include Sekong, Srepok, Sesan, Nam Ngum, Sesan, Nam Mun, and Nam Theun.

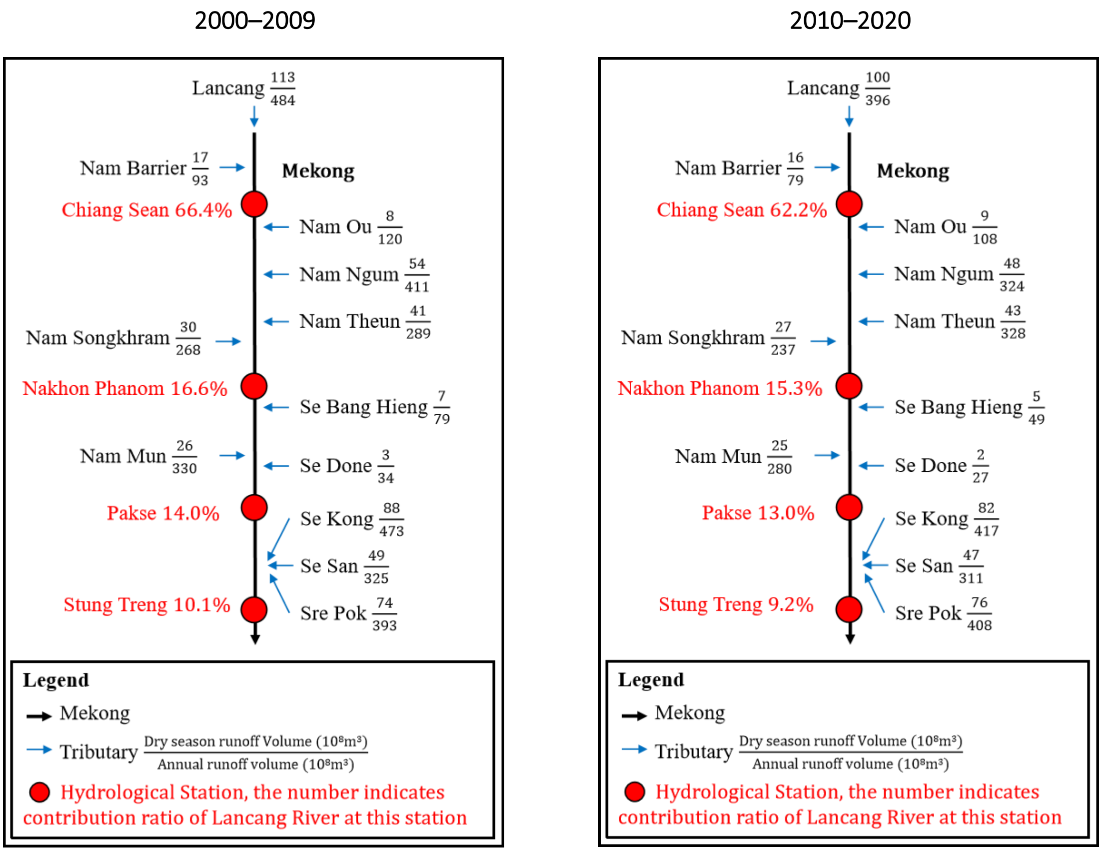

Figure 24. Simulated dry season over annual volume of major tributaries and contribution ratio of Lancang River from the THREW model for 2000–2009 (left) and 2010–2020 (right)

17 'Natural runoff' is defined in this case as the runoff or flow generated from the THREW model through natural rainfall-runoff process without considering any water infrastructure development.

The seasonal contribution ratio can be found in Annex K – Contribution ratio of the simulated seasonal volume of the major tributaries to mainstream stations along the Mekong River for 2000–2009 and 2010–2020.

For 2000–2009, the proportion of dry season runoff at Stung Treng were from the Lancang River (15.5%), Sekong (12.0%), Srepok (10.1%), and Nam Ngum (7.3%), with the latter three adding up to a higher contribution than the Lancang River. In the wet season, while the Lancang stretch contributed 9.1%, these tributaries (9.4% from Sekong, 8.8% from Nam Ngum, and 7.8% from Srepok) supplied more than those from the Lancang River.

For 2010–2020, in the dry season, the Lancang River runoff contributes 14.5% to flows at Stung Treng. The tributaries that account for a higher proportion of runoff in the dry season are the Sekong (12.0%), Srepok (11.1%), and Sesan (6.8%). The Sekong-Sesan-Srepok contributed higher than the Lancang River. In the wet season, the Lancang stretch contributes 8.2%. The tributaries (9.2% from Sekong, 9.1% from Srepok, and 7.9% from Nam Theun) supplied more than those from the Lancang River.

Table 7. Contribution ratio of the simulated annual volume of the major tributaries to mainstream stations from the THREW model for 2000–2009 and 2010–2020

Contributing tributaries to mainstream stations (%)	Lancang	Nam Barrier	Nam Ou	Nam Ngum	Nam Theun	Nam Songkhram	Se Bang Hieng	Nam Mun	Se Done	Sekong	Sesan	Srepok
2000–2009												
Chiang Saen	66.4	12.8	–	–	–	–	–	–	–	–	–	–
Luang Prabang	42.1	8.1	10.4	–	–	–	–	–	–	–	–	–
Chiang Khan	34.3	6.6	8.5	–	–	–	–	–	–	–	–	–
Nong Khai/Vientiane	32.7	6.3	8.1	–	–	–	–	–	–	–	–	–
Nakhon Phanom/Thakhek	16.6	3.2	4.1	14.1	9.9	9.2	–	–	–	–	–	–
Mukdahan/Savannakhet	16.3	3.1	4.0	13.8	9.7	9.0	–	–	–	–	–	–
Pakse	14.0	2.7	3.5	11.9	8.4	7.7	2.3	9.5	1.0	–	–	–
Stung Treng	10.1	1.9	2.5	8.5	6.0	5.6	1.6	6.9	0.7	9.8	6.7	8.2
2010–2020												
Chiang Saen	62.2	12.4	–	–	–	–	–	–	–	–	–	–
Luang Prabang	42.2	8.4	11.6	–	–	–	–	–	–	–	–	–
Chiang Khan	34.4	6.9	9.4	–	–	–	–	–	–	–	–	–
Nong Khai/Vientiane	32.5	6.5	8.9	–	–	–	–	–	–	–	–	–
Nakhon Phanom/Thakhek	15.3	3.1	4.2	12.5	12.6	9.1	–	–	–	–	–	–
Mukdahan/Savannakhet	14.9	3.0	4.1	12.2	12.4	8.9	–	–	–	–	–	–
Pakse	13.0	2.6	3.6	10.7	10.8	7.8	1.6	9.2	0.9	–	–	–
Stung Treng	9.2	1.8	2.5	7.5	7.6	5.5	1.1	6.5	0.6	9.7	7.2	9.5

Note: Simulated volume at Jinghong is used for a flow contribution from the Lancang River.

3.5.5 Relative impact of changing climate using the THREW model

One of the key objectives of Phase 1 of the Joint Study was to distinguish the effects of the development of the LMRB from the changing climate conditions on runoff. With the THREW model calibrated against flows for 2000–2009 to obtain the model parameters, this was done by comparing the observed and simulated streamflow from the THREW model for the periods of 2000–2009 and 2010–2020 with the following three scenarios:

- Scenario 1: Comparing the observed 2000–2009 and observed 2010–2020 streamflow provides an indication of the **combined effects** of climate conditions and the development of the basin;
- Scenario 2: Comparing the observed 2010–2020 and simulated 2010–2020 streamflow provides an indication of the **impacts of the development** of the LMRB over the last decade; and
- Scenario 3: Comparing the simulated 2000–2009 and simulated 2010–2020 streamflow provides an indication of the **effects of the different climate conditions** over the last decade.

To be noted, the observed and simulated streamflow for the period of 2000–2009 by the THREW model is rather identical as shown in **Figure 22** and **Figure 23**. To simplify the analysis, the observed 2000-2009 streamflow is used for comparison in **Figure 25**.

Figure 25 presents the monthly streamflow for the three scenarios. In 2010–2020, flows are lower than those in 2000–2009 at all stations (Scenario 3). When the development is taken into account (Scenario 2), there is a shift of water volume from the wet season to the dry season for 2010–2020, compared with 2000–2009.

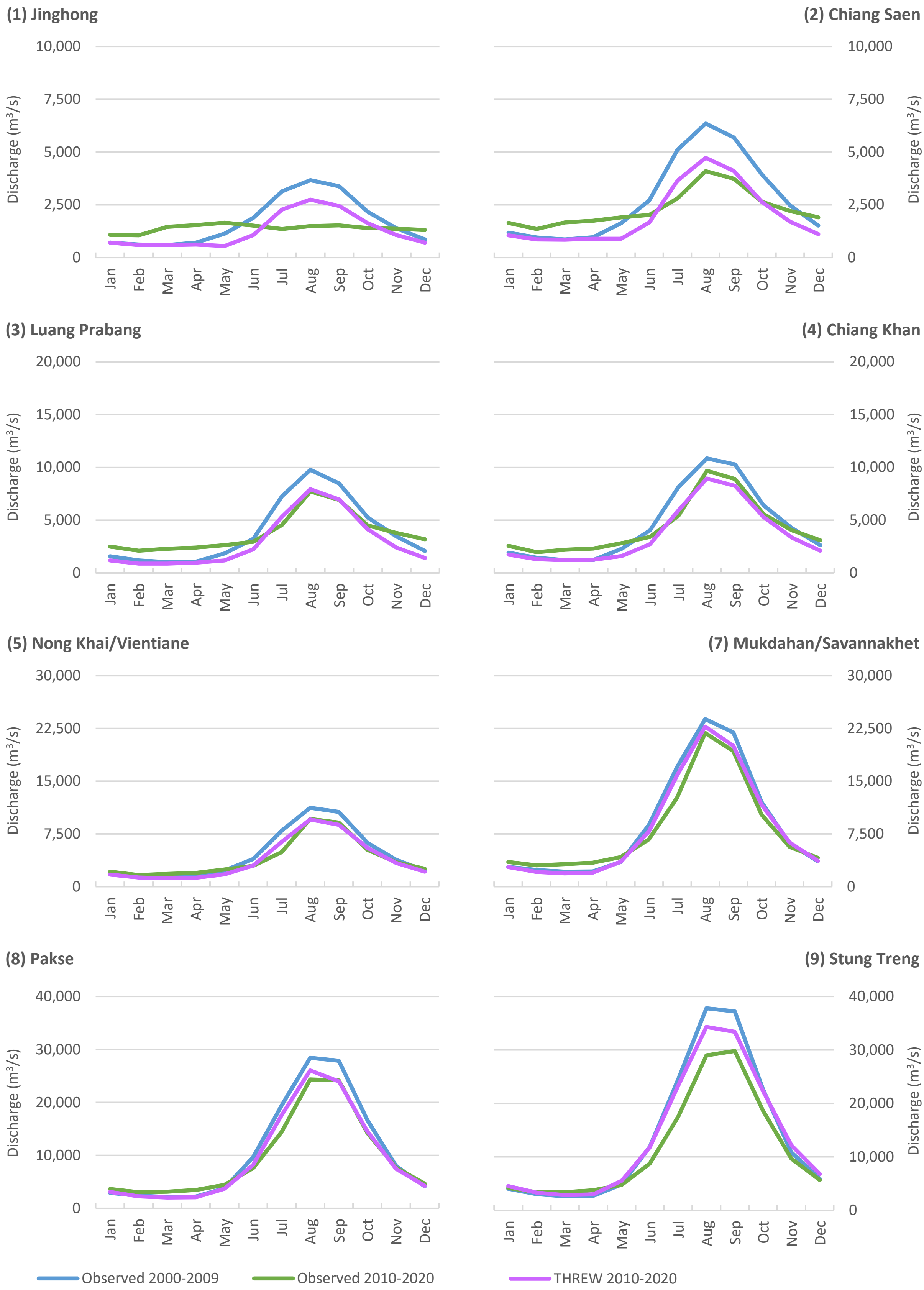

Figure 25. The monthly hydrographs of the average observed discharge for 2000–2009 (blue) and 2010–2020 (green) and from the THREW model (purple) at key hydrological stations

3.5.6 Scenario analysis using the SWAT/Source models

Another way of separating the impacts of water resource development and climate is to run the Source water system model with two scenarios: (1) all water uses sectors, including storage for hydropower, irrigation, and domestic water use, and (2) only irrigation[18] and domestic water uses. The monthly average flows for 2000–2009 and 2010–2020 for these scenarios highlight differences in flow patterns due to the development and climate. The monthly hydrographs displaying the difference between the two scenarios for key mainstream stations are depicted in **Figure 26**.

There are significant differences between the scenarios for the upstream stations at Jinghong and Chiang Saen during 2010–2020. This becomes increasingly less clear further downstream, potentially due to the impacts of using the generalised rule curves for the storage on the Mekong tributaries and/or the fact that there are more unregulated inflows from the downstream tributaries.

These scenario analyses show that the development of storage has an impact on mainstream flows and that this follows the accepted wisdom that water is stored in the wet season to provide for assured generation in the dry season.

The simulated results from the THREW and SWAT/Source models support each other and provide consistent trends of the hydrological impacts of the water resource development and climate. The two model packages demonstrate that the development of water storage has increased the low water levels in the dry season and decreased the high flow in the wet season in the whole basin. This is more evident at upstream stations but less evident further downstream, where the contributions from the unregulated portions of the tributaries are greater.

[18] The MRC Council Study concluded that the basin irrigation has negligible impact on wet season flows of the Mekong mainstream. Dry season flows slightly increased due to the irrigation (MRC, 2018).

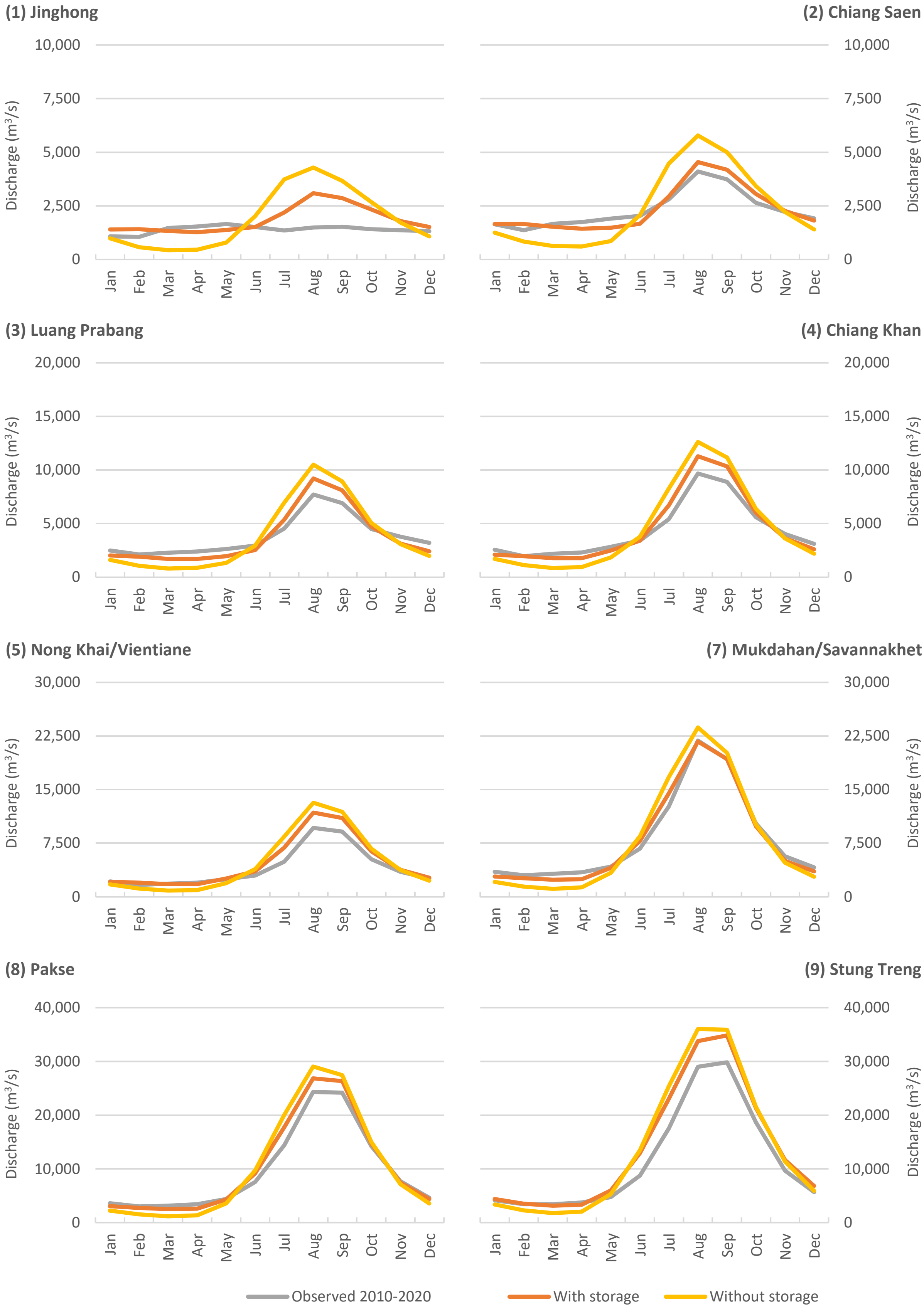

Figure 26. The monthly hydrographs from the Source water system model showing the average observed discharge (grey) and the average discharge with (orange) and without (yellow) storage at key hydrological stations for 2010–2020

3.6 Changes in meteorological drought patterns

Based on the long-term CRU TS dataset, a previous study found that severe and exceptional droughts occurred more frequently during 1961-2019 compared to 1901-1960. The highest frequency of severe meteorological drought occurred in the middle and upper areas of the Lancang region, reaching more than 12%, which is confirmed by the result based on CHIRPS dataset. Also, the proportion of drought occurring in the dry season is significantly higher than that in the wet season (Tian et al.,2020).

The analysis of these SPI and SPEI datasets is consistent at both seasonal and annual scales (**Figure 27** and **Figure 28**). Generally, the dry and wet seasons show trends toward more severe droughts over large areas of the LMRB. Furthermore, the period of 1950–2021 shows considerable spatial changes in both these indexes when compared to 120-year data (1901–2021). This suggests that the trend towards 'drier' conditions is more recent and is likely to be related to the changing climate.

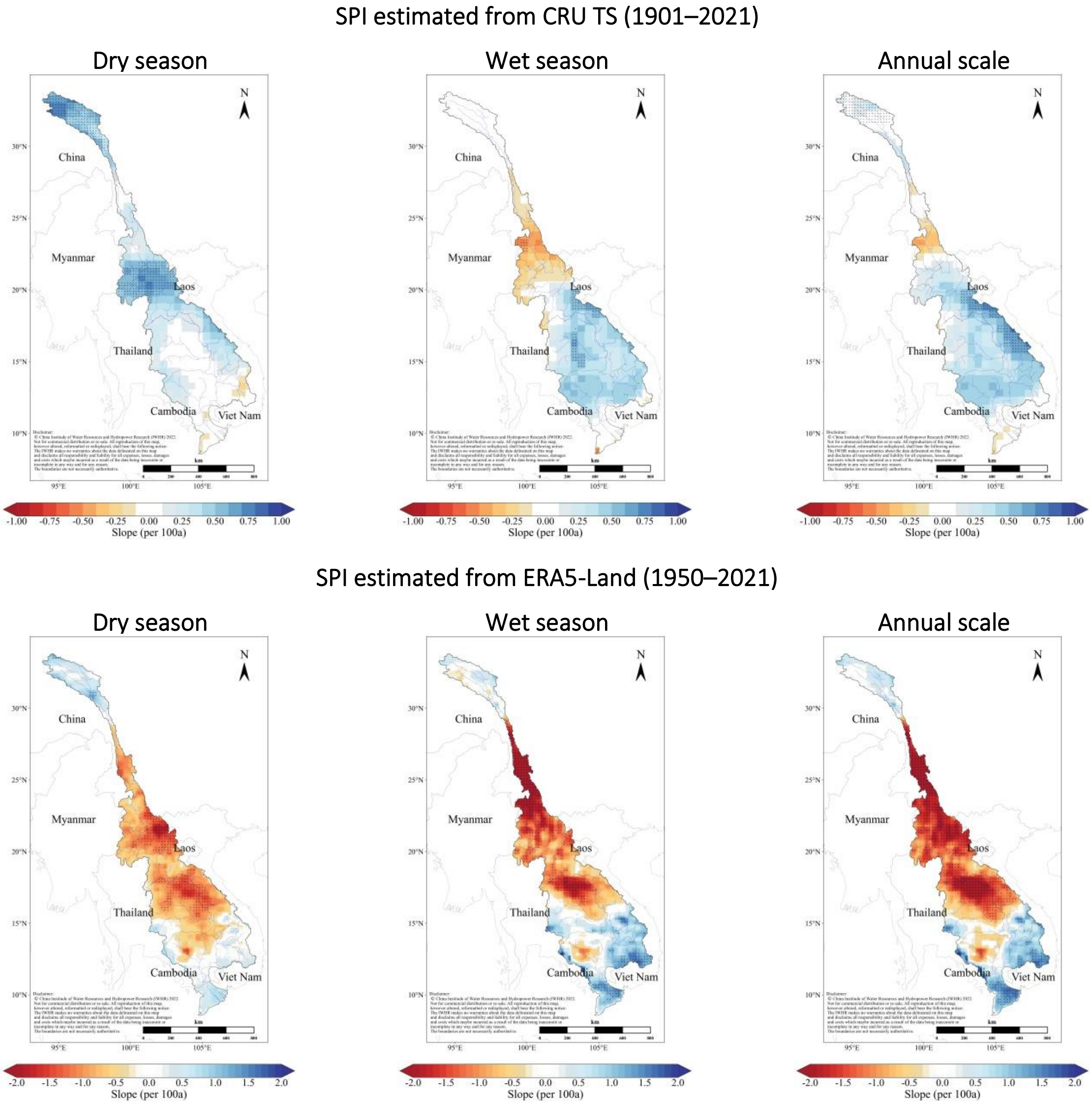

Figure 27. Historical drought trends by SPI index. Red indicates intensifying droughts, while blue means less severe drought conditions

The SPI and SPEI estimated from CRU TS (1901–2021) reveal a trend towards more intense droughts in the southern Lancang Basin, northern Mekong Basin, and southern Mekong Basin in Viet Nam. The SPI and SPEI calculated from ERA5-Land (1950–2021) suggest that even more intense droughts could occur in the southern Lancang Basin, northern Mekong Basin, and the area around the Tonle Sap Lake in Cambodia in both the wet and dry seasons in future.

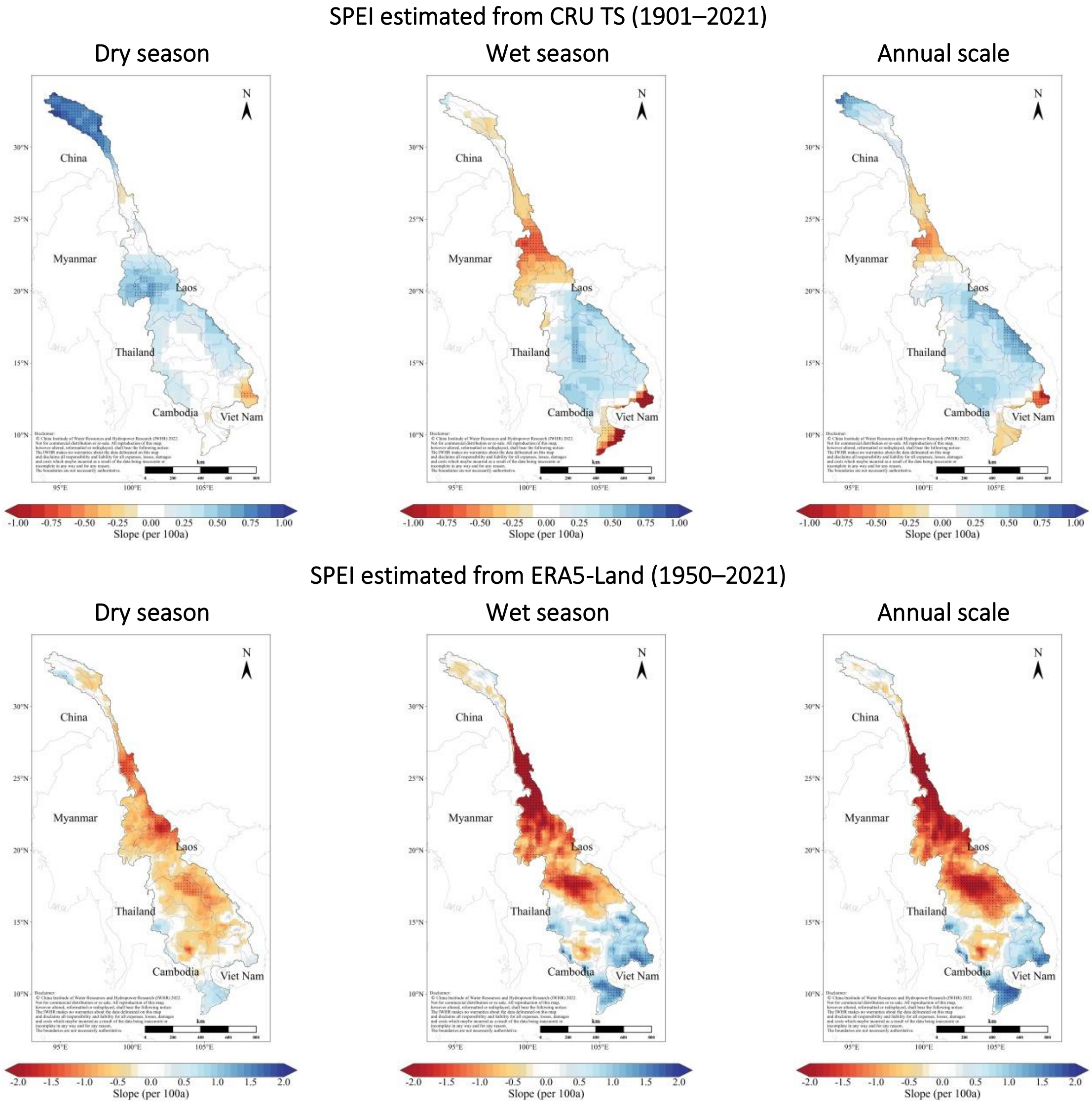

Figure 28. Historical drought trends by SPEI index. Red indicates intensifying droughts, while blue means less severe drought conditions

3.6.1 Drought frequency, duration, and severity

Frequency

The frequency of droughts with various thresholds was analysed using SPI and SPEI indices based on the ERA5-Land dataset. The changes in annual meteorological drought frequency between 2000–2009 and 2010–2020 are illustrated in **Figure 29**. Seasonal variation in drought frequency can be seen in Annex L – Variation of drought frequency between 2000–2009 and 2010–2020. Additionally, the drought types are classified in Annex G – Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI).

The period from 2010–2020 showed significant increases in drought frequency in the middle and lower reaches of the Lancang basin and the middle reach of the Mekong. Similarly, the lower part of the Lancang, upper Mekong sections, and the middle areas of Cambodia show trends towards more frequent and more severe droughts frequencies when compared with the 2000–2009 period.

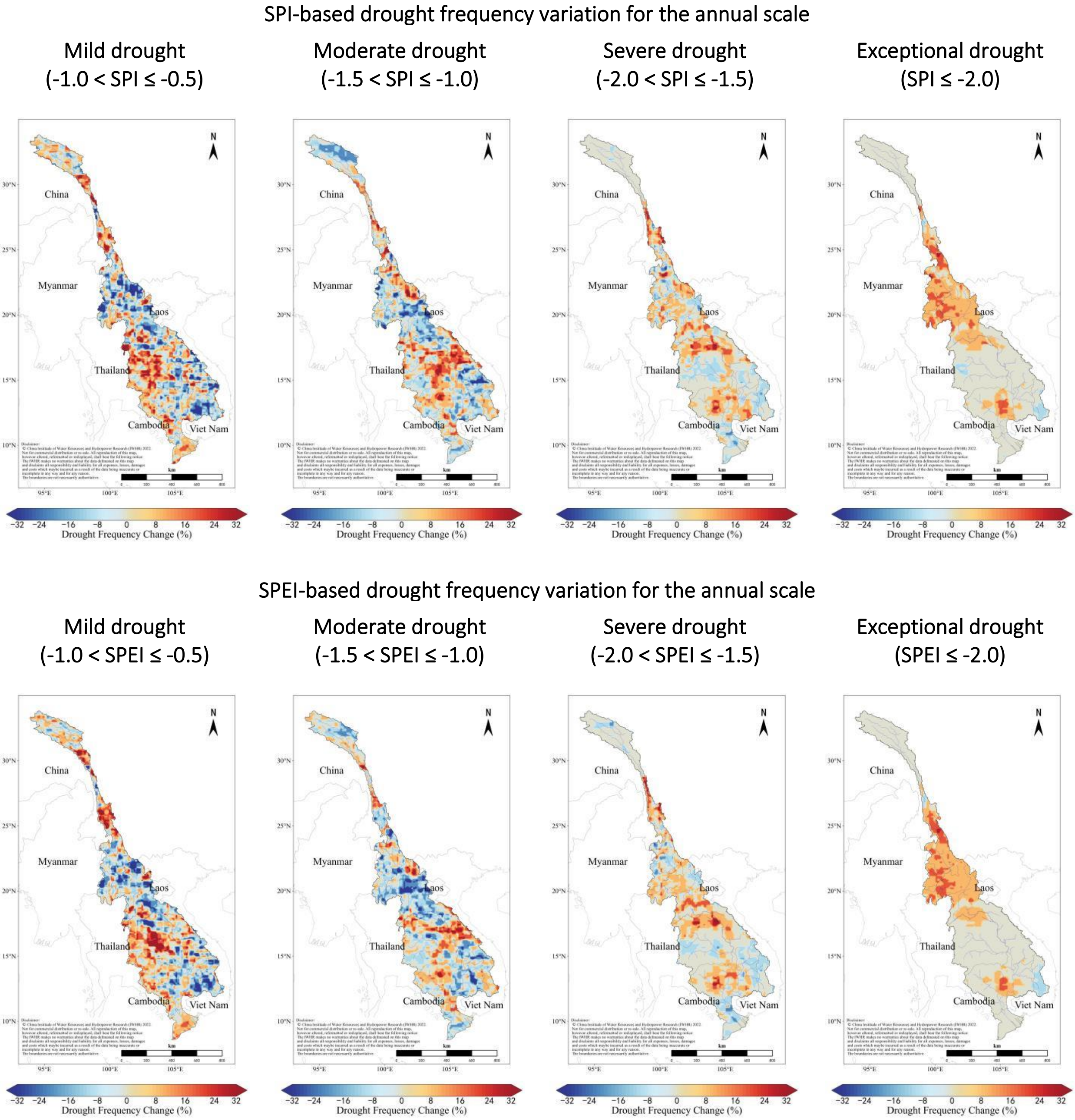

Figure 29. Variation of annual drought frequency between 2000–2009 and 2010–2020 based on ERA5-Land dataset. Red indicates more frequent droughts, while blue means less frequent drought conditions

Duration

Drought duration was estimated for SPI and SPEI from the ERA5-Land dataset. The changes in drought duration between 2000–2009 and 2010–2020 are shown in **Figure 30**. The changes in seasonal scales of drought duration are presented in Annex M – Variation of drought duration between 2000–2009 and 2010–2020.

Mild drought durations (-1.0 < SPI/SPEI ≤ -0.5) tend to have longer durations over large areas of the basin, especially in the lower part of the basin. Severe (-2.0 < SPI/SPEI ≤ -1.5) and exceptional (SPI/SPEI ≤ -2.0) droughts were also prolonged in most parts of the basin, and it is noticeable that the exceptional drought was prolonged in the middle part of the basin.

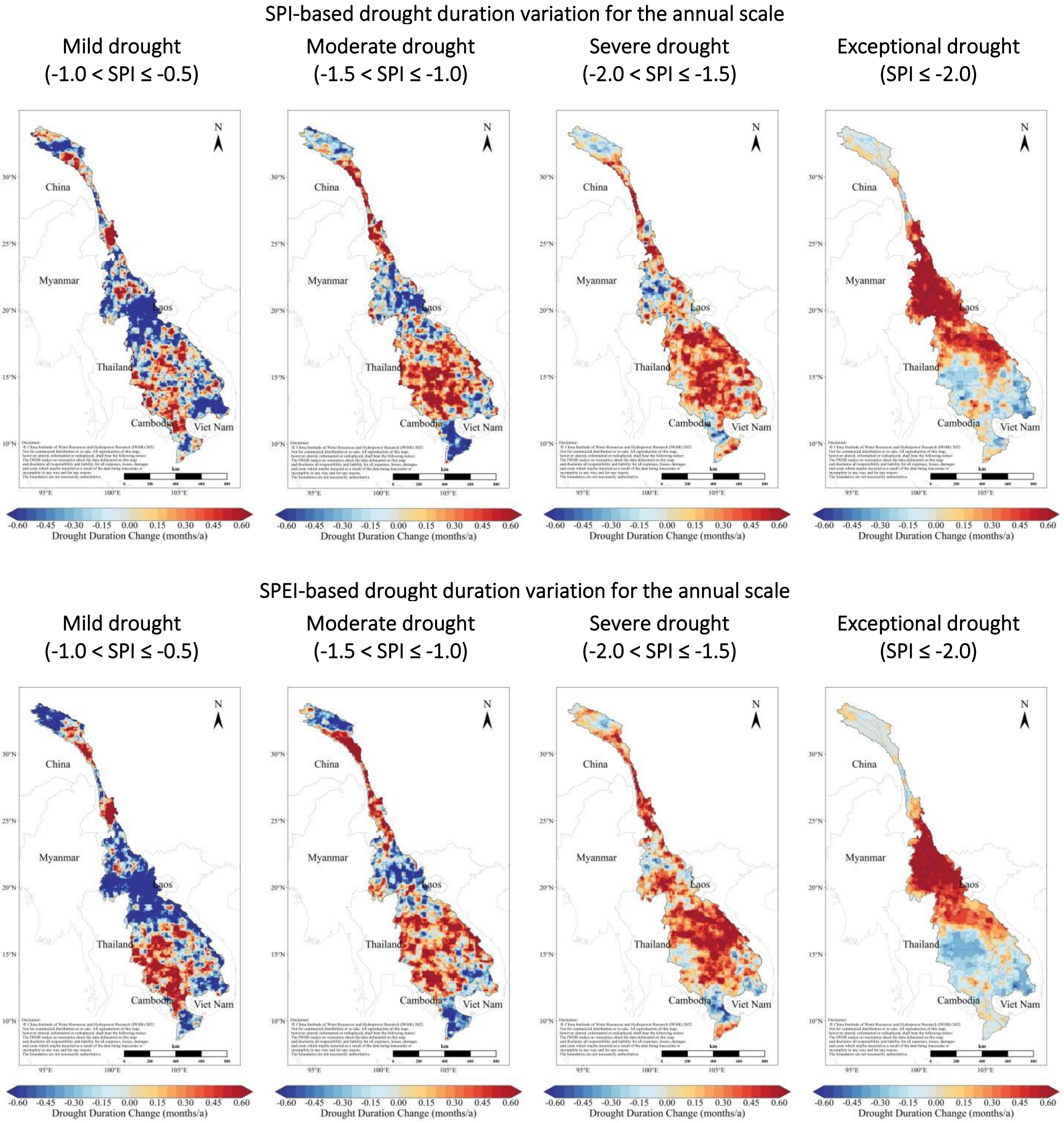

Figure 30. Variation of annual drought duration between 2000–2009 and 2010–2020 based on ERA5-Land dataset. Red indicates where drought durations were prolonged, while blue means drought periods were shortened

Intensity

Like drought frequency and duration, the drought intensity was analysed using the SPEI and SPI indices based on the ERA5-Land dataset for the period of 2000–2020 (**Figure 31**). Seasonal variations in drought frequency are displayed in Annex N – Variation of drought intensity between 2000–2009 and 2010–2020.

The period 2010–2020 marked a small decrease in the intensity, meaning more severe droughts for the severe/exceptional droughts categories in most parts of the basin. The intensity of exceptional droughts decreased in the lower Lancang Basin and the upper Mekong. The changes in drought intensity of all grades (SPI/SPEI ≤ -0.5) for these two periods have large spatial heterogeneity.

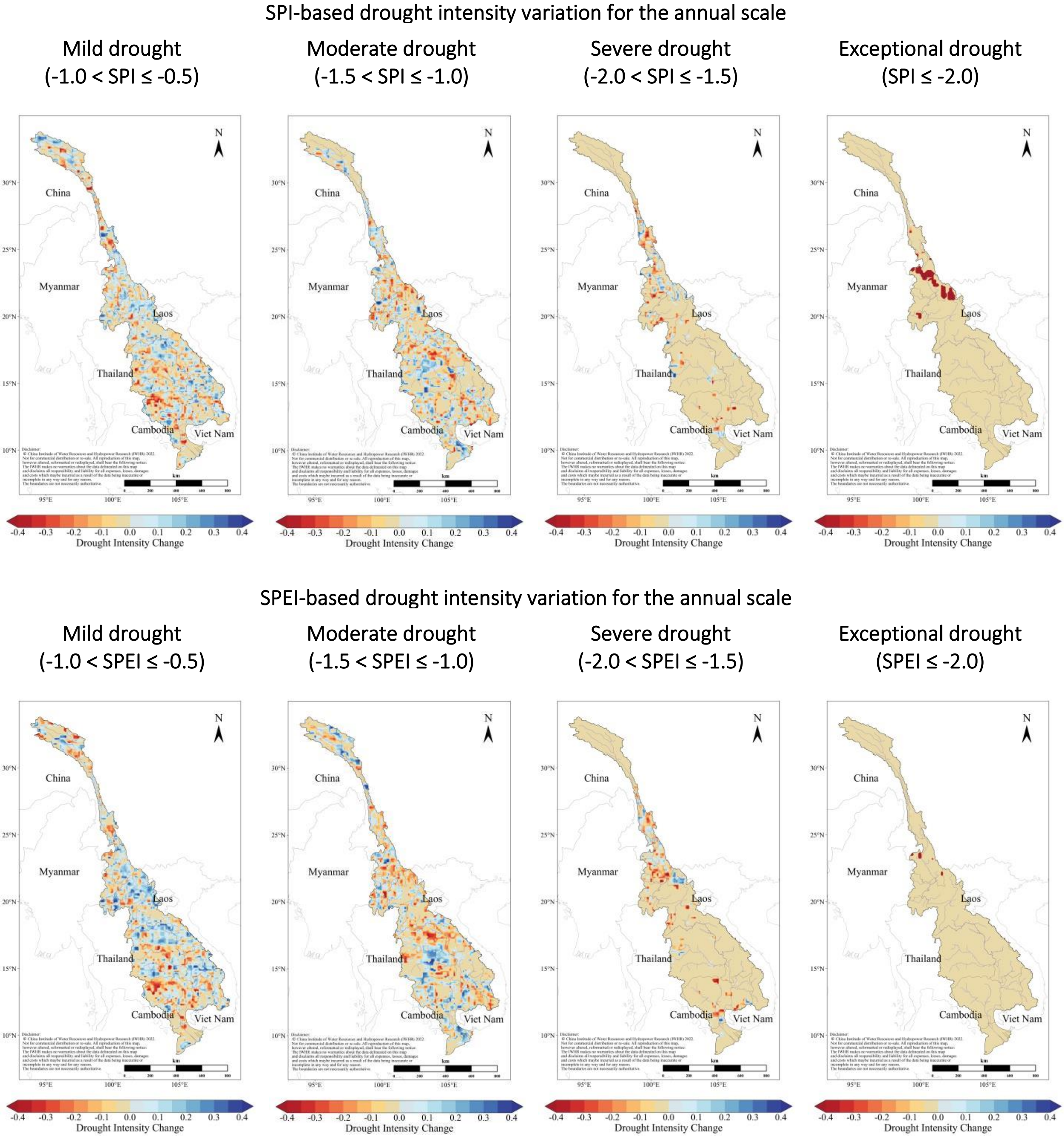

Figure 31. Variation of annual drought intensity between 2000–2009 and 2010–2020 based on ERA5-Land dataset. Red indicates drought intensified, while blue means the opposite

3.6.2 Relation of meteorological and hydrological droughts

To investigate the relation between the meteorological and hydrological droughts in the Mekong River Basin, drought frequency changes were estimated using CHIRPS-based annual SPI (for meteorological drought) and VIC-model-based annual SRI (for hydrological drought) between 2000–2009 and 2010–2020.

Figure 32 reveals a remarkable similarity in drought frequency changes of the meteorological and hydrological droughts over the Mekong River Basin. The frequency of both meteorological and hydrological droughts increased intensively during 2010–2020 compared to 2000–2009. Moderate and severe droughts have the most significant frequency spatially. The results also indicate that meteorological factors play a dominant role in hydrological processes.

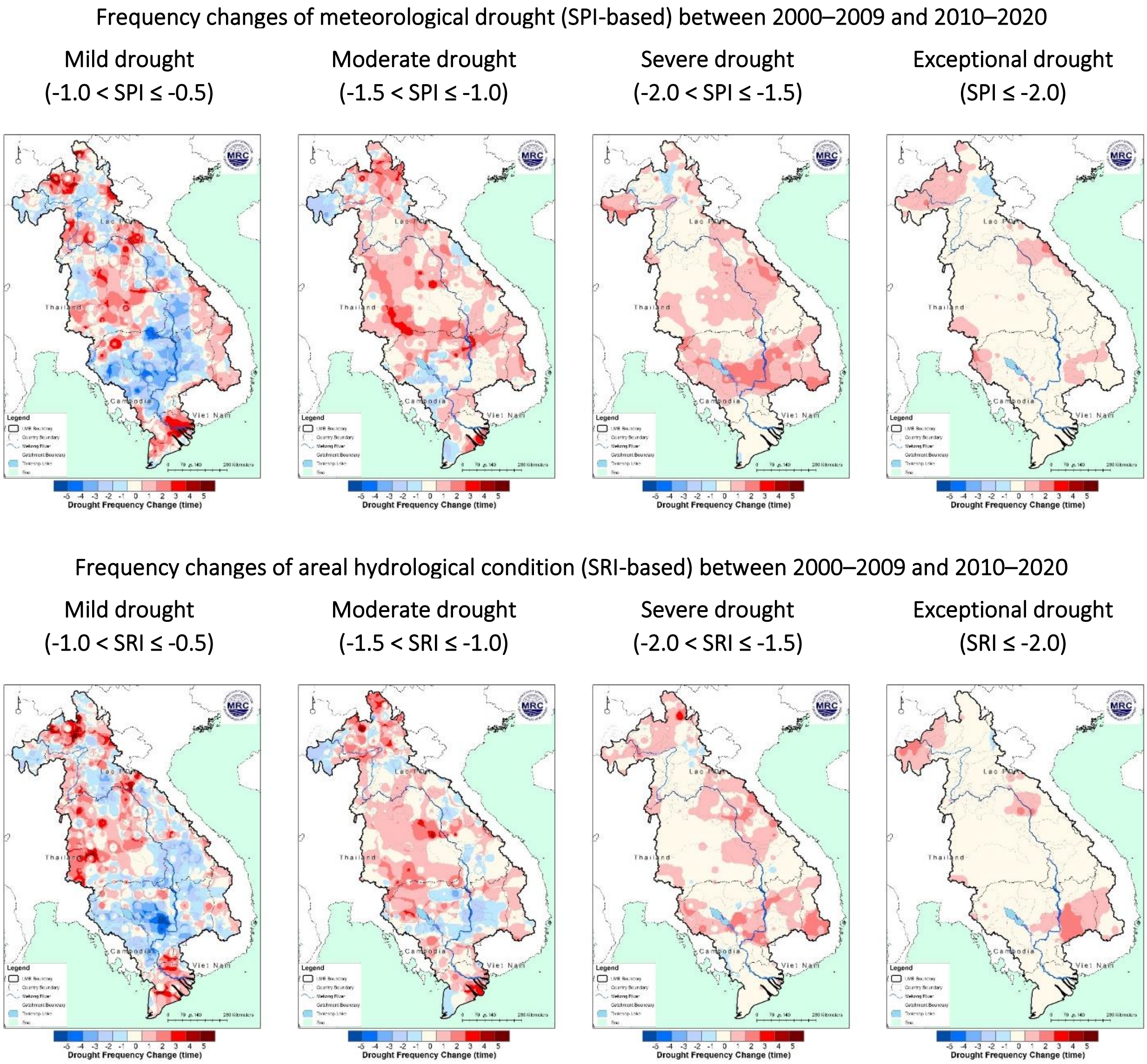

Figure 32. Frequency changes in meteorological droughts (SPI by CHIRPS) and areal hydrological conditions (SRI by VIC model) drought frequency changes between 2000–2009 and 2010–2020. Red indicates more frequent droughts, while blue means less frequent droughts

More specifically, in the last decade (2010–2020), more frequent droughts in mild/moderate than severe/exceptional droughts occurred. Mild droughts increased in the northern, middle (mainly Thailand), and the southern (Central Highland of Viet Nam and Delta). On the contrary, they significantly less occurred in Cambodia and south Lao PDR. While severe droughts increased in the middle and lower parts of the Mekong River Basin, the exceptional drought did not change much in the recent decade.

Furthermore, a great degree of consistency of drought frequency distribution of SPIs estimated from CRU TS, ERA5-Land (**Figure 29**), and CHIRPS (**Figure 32**) reveals that the LMRB has been exposed to more frequent droughts in the last decade.

3.6.3 Drought events and causes

Three events from 2000–2020 were selected for further investigation of the driving forces and characteristics of drought in the LMRB. These are the droughts of 2004-2005, 2016, and 2019–2020.

The drought of 2004–2005

The drought of August 2004 extended into the dry season of 2005 due to the earlier ending of the wet season in October 2004. This was widespread across the basin. This drought is among the most severe events in recent years, which led to the failure of wet season rice cultivation, damaged farming, and led to food shortages throughout the Basin. This is clearly seen from the NDVI or vegetation anomaly[19] in March 2005 (**Figure 33**). In drier periods, plant growth is less dense and less healthy than normal. These show up as shades of brown, whereas areas with denser-than-average vegetation are in shades of green.

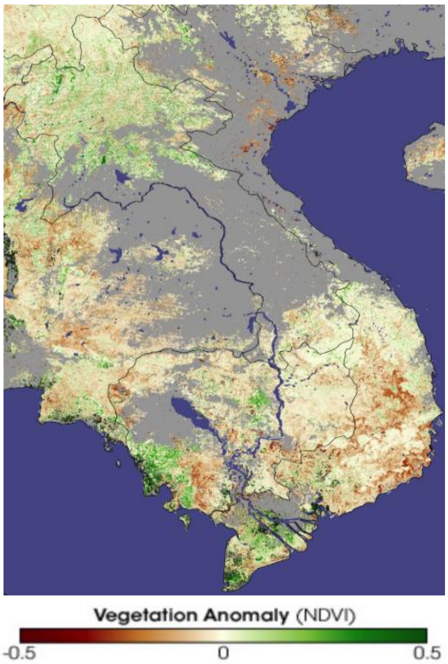

Figure 33. Vegetation anomaly in March 2005

This severe drought hit the Yunnan province in China (the middle and lower part of the Lancang River) in the spring and early summer of 2005 and was the most severe drought recorded over the preceding 50 years (Liu et al., 2007). The drought also affected 14 out of 24 provinces in Cambodia, resulting in food shortages for 500,000 people. In the Cuu Long Delta, more than 104,000 hm^2 of rice paddy was damaged, and gross drought losses amounted to some 42 million USD. In Thailand, 63 out of the 76 provinces were affected. Across the country, 9 million people's lives were affected, and irrigation water was restricted (and even prohibited) to ensure domestic water supply (Liu, 2020).

The evolution of this drought and the accompanying precipitation and temperature conditions are illustrated in Annex O – SPEI, precipitation and temperature anomaly for drought in 2004–2005. This annex shows that precipitation and temperature anomalies were noted since October 2004 (marking an earlier end of the wet season), and the precipitation was less than the long-term average until May 2005. This is confirmed by the SPEI analysis.

[19] NASA Earth Observatory: Drought in Southeast Asia–https://earthobservatory.nasa.gov/images/14733/drought-in-southeast-asia, accessed on 21 September 2022.

The drought of 2016

Another major drought event occurred in 2016. Extreme high temperatures and a strong El Niño event created abnormally dry weather in 2016. A severe drought developed in the LMRB in early 2016. The water level of the Lancang-Mekong River dropped to its lowest levels in the previous 90 years. This brought considerable damage to agricultural production over the region and affected the livelihoods of many across the Basin. The drought was so severe that China implemented emergency water releases from the Lancang hydropower cascade to the Mekong River from 15 March to 31 May 2016. These supported navigation, environmental flows, and mitigated saltwater intrusion in the delta (MRC & MWR, 2016). A more detailed analysis of this drought can be found in the Joint Observation and Evaluation of the Emergency Water Supplement from China to the Mekong River[20] (2016).

The precipitation deficit in the middle and lower part of the LMRB started in February 2016, and higher than normal temperatures occurred from March 2016. The drought extended from the southern regions to the northern regions of the Basin gradually, reaching a peak in April 2016 (Annex P – SPEI, precipitation and temperature anomaly for drought in 2016). However, temperatures remained high throughout the year. With the return of more normal precipitation, the drought gradually eased from the south to the north of the LMRB.

Drought of 2019–2020

Globally the WMO recorded the warmest June on record in 2019, and 2019 as a whole was the 3rd warmest year over a 170-year record. The MRCS reported low rainfall in the early wet season of 2019 in its weekly flood situation reports since June. The severe drought started in the wet season of 2019 and lasted until the wet season of 2020. It brought unprecedented low water levels in the Lancang-Mekong River, with the lowest levels in more than 60 years being recorded. This resulted in knock-on impacts on fisheries and agricultural production and hence on people's livelihoods throughout the basin (MRC, 2022). A more detailed analysis of this drought can be found in the Mekong Low Flow and Drought Conditions in 2019–2021[21] (2022).

The SPEI, precipitation anomaly, and temperature anomalies of 2019 and 2020 are presented in Annex Q – SPEI, precipitation and temperature anomaly for drought in 2019–2020. This shows large areas of precipitation deficits and higher temperatures over this period, indicating the onset of the drought at the beginning of 2019, especially in Lao PDR and Cambodia. Higher temperatures persisted throughout the year and for most of 2020 in many parts of the LMRB. The precipitation deficit reached its peak in April 2019, and severe drought was prevalent over most of the basin. The extreme drought over the basin, especially in the lower Lancang and upper Mekong regions, persisted in the last eight months of 2019. This made 2019 the most severe drought year in the last 120 years (Tian et al., 2020). The drought continued until September 2020 and ended in October with abundant rainfall over most of the Basin.

The impact of El Niño on droughts

Various studies suggest that there are four leading causes for droughts in the LMRB: climate change, low rainfall, hot and dry weather (high evaporation), and the El Niño phenomenon (Keovilignavong et al., 2021). During an El Niño event, from December to February, precipitation is reduced over the Basin,

[20] Mekong River Commission and Ministry of Water Resources of the People's Republic of China (2016). Technical Report–Joint Observation and Evaluation of the Emergency Water Supplement from China to the Mekong River. Mekong River Commission, Vientiane, Lao PDR. https://www.mrcmekong.org/resource/ajg7si

[21] Mekong River Commission (2022). Technical Report–Mekong Low Flow and Drought Conditions in 2019-2021. Mekong River Commission, Vientiane, Lao PDR. https://www.mrcmekong.org/assets/Publications/LowFlowReport20192021.pdf

and temperatures are higher than usual in the following March to August (Guang & Gao, 2012). Sam et al. (2019) also noted a strong relationship between El Niño events and drought in the Mekong Basin.

The drought events described above were also associated with El Niño events. The onset and end of the El Niño events over the last 22 years are highlighted in **Figure 34**. The drought in 2016 coincides with the super El Niño event of 2015–2016, which was the biggest event since 2000. The 2015–2016 El Niño peaked in January 2016, was long-lasting, and was larger in area. The side-by-side comparisons of Pacific Ocean Sea surface height anomalies[22] caused by the El Niño phenomenon in 2004–2005, 2015–2016, and 2018–2019 are illustrated in **Figure 35**. Higher sea temperatures, and hence a greater volume of water, are a clear indicator of El Niño events. The larger areas of elevated sea levels in 2015 and 2016 are clear in **Figure 35**.

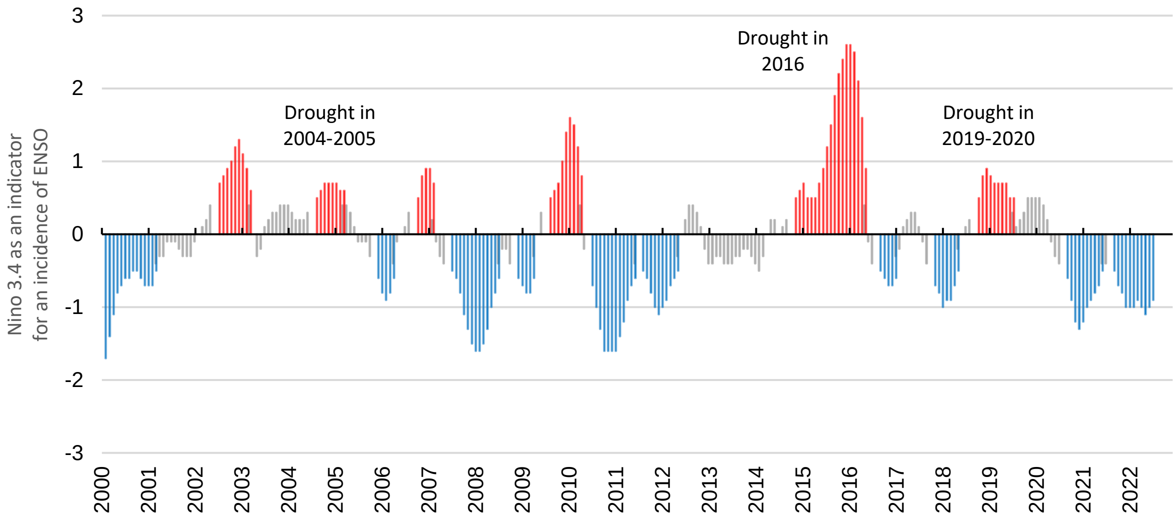

Figure 34. Dynamics of Nino 3.4 as an indicator for an incidence of ENSO for 2000–2022

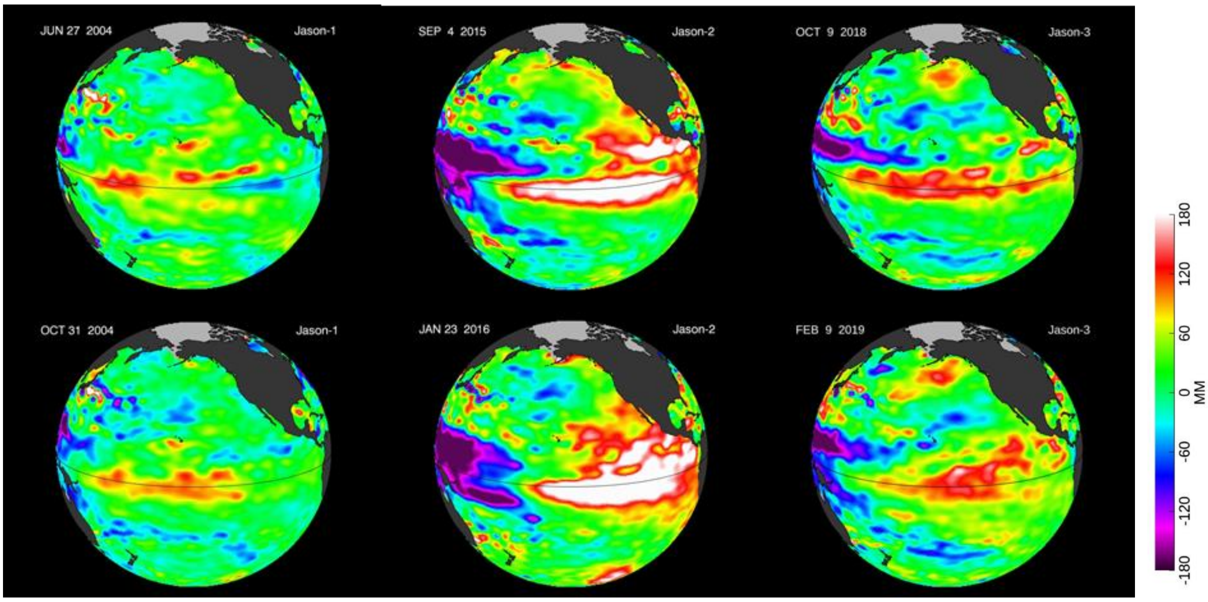

Figure 35. Comparisons of Pacific Ocean Sea surface height anomalies caused by the El Niño 2004-2005, El Niño 2015-2016 and El Niño 2018-2019

22 Jet Propulsion Laboratory, Ocean Surface Topography from Space, El Niño/La Niña Watch & PDO. https://sealevel.jpl.nasa.gov/data/el-nino-la-nina-watch-and-pdo/data/

4 OPPORTUNITIES FOR CLIMATE CHANGE ADAPTATION MEASURES

For thousands of years, residents in the Lancang-Mekong Basin have adapted to the characteristics of water resources in the basin and formed their own way of life and production. However, with the improvement of production and living standards, the relationship between people and water resources is also changing. More people are using the shared water resources to support their livelihoods leading to increases in irrigation, energy production, fisheries, and shipping. The changing environmental state of the basin is also affected by increasingly severe floods and droughts. Building a common understanding of the drivers of these changes is critical to future joint operational management and development of the LMRB.

While addressing the challenges of climate change, the water experts in the basin are exploring a way to utilize water resources in a more equitable manner, reducing the harmful effects of development and maximising the joint benefits that can be derived from the development of the basin. The relationship between people and water involves all aspects of social, economic, and environmental systems. In terms of water resources development and utilization, especially reservoir and dike construction, developed countries are far ahead. Water resource management in developed countries has gone through the process of pollution first, then treatment, and finally, the practice of water environment friendliness (i.e., Environmental Kuznets Curve, EKC). In view of the water resources management experience of developed countries and the fact that raw materials, production, and pollution emissions are mainly in colonies and underdeveloped states in the industrialization of the developed countries, the Lancang-Mekong River Basin, in the context of rapid economic and social development, needs to make more efforts to pursue the sustainable development of water resources.

4.1 The hydro-political supporting environment

Any measures to adapt to the impacts of climate change (droughts and floods) and the associated increasing levels of storage in the LMRB will be applied within the regional hydro-political context. In this regard, the foreign policies of all six riparian States are founded on non-interventionism. Non-interventionism is a foreign policy doctrine that opposes interference in other countries' domestic politics and affairs. This is, however, not necessarily opposed to making international commitments[23]. In the hydro-political context, this means that all the riparian States conform, in general, to the customary international water law principles of cooperation, reasonable and equitable use of the shared waters, and avoidance of significant harm. The MRC theme of “One Mekong, One Spirit” and the LMC theme of “Shared River, Shared Futures” share a similar concept of strengthening mutual benefits through consultation with one another to ensure a balance of interests and responsibilities of participating countries while respecting the decision-making of each member country on its water resources management.

The four countries of the Mekong River Basin have signed the 1995 Mekong Agreement to formalise these principles. With the establishment of LMC/MLC in 2016, the six riparian countries have taken steps to drive basin-wide cooperation to address water-related challenges on these principles. The biennial LMC Leader’s Meetings and annual Foreign Ministers’ Meetings as well as the Ministerial Meeting of

[23] As opposed to isolationism which opposes making any international commitments.

LMC Water Resources Cooperation have provided strong political and policy leadership in this regard. The Vientiane Declaration of the 3rd LMC Leaders' Meeting of August 24, 2020, decided to further enhance pragmatic cooperation in areas such as climate change adaptation, dam safety, drinking water safety, flood and drought disaster management, and support establishment of the Lancang-Mekong Water Resources Cooperation Information Sharing Platform. At the 7th Foreign Ministers' Meeting of July 4, 2022, the Ministers stressed the key and fundamental role of water resources cooperation in building climate resilience and ensuring flood and drought prevention and management, food and energy security, water supply, ecological protection, supporting sustainable economic and social development and serving people's livelihood. The Joint Statement of the 1st LMC Ministerial Meeting of Water Resources Cooperation indicated that the water ministers will work together to enhance the capacity of the six member countries in the prevention and mitigation of water-related disasters and adaptation to climate change through increased investment, improved risk assessment, joint studies, and knowledge sharing.

These developments have created a more favourable hydro-political context for the six riparian countries to jointly address basin-wide challenges. Notable progress is evidenced by the events of 2016 and 2019, where China made supplementary releases to mitigate the impacts of the droughts (as detailed above). Similar extreme low flow events have seen releases made from the Lancang cascade to support navigation in the northern Mekong reaches[24]. The MOU signed between the LMC Water Center and MRC and this present Joint Study also underpin the growing recognition that increased cooperation is needed.

4.2 The hydrological context

Conceptually, water in the Lancang-Mekong mainstream can be put to several 'uses', as illustrated in **Figure 36**. Managing the flows on the mainstream to address the impacts of climate change means balancing the flows through these channels.

For many years, storage development has been the go-to solution to drought management, i.e., to store water in wet years and make it available in dry years. This means storing surplus flows (not needed for immediate needs) to provide resilience for future low flows. Drought-prone basins, therefore, have active storage capacity several times the volume of the Mean Annual Runoff. Examples are the Murray-Darling, Colorado, and the Orange-Senqu Rivers. However, in the LMRB, only some 9% of the MAR is currently available as *active* storage. While there are possible opportunities to increase the overall storage in the basin in the long-term drought management in the Basin is likely to be limited

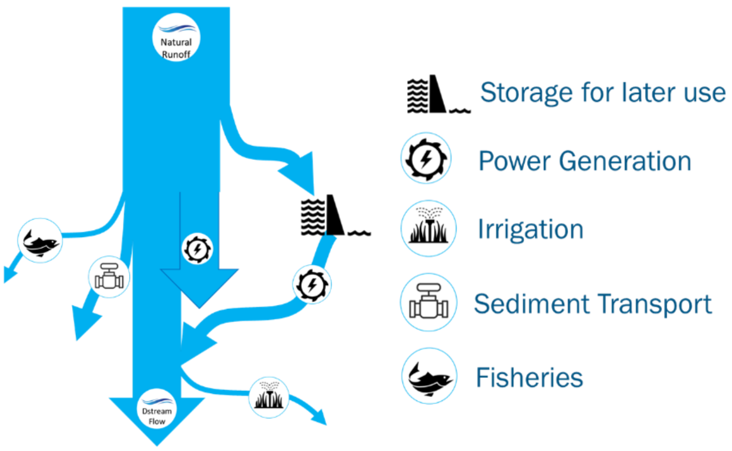

Figure 36. A conceptual split of the flows between several channels to support climate adaptation for the Lancang/Mekong mainstream

24 https://www.bangkokpost.com/thailand/general/1424767/stranded-boats-clog-mekong & https://www.bangkokpost.com/thailand/general/461825/china-tipped-to-top-up-dried-up-mekong

to intra-annual operations, i.e., releasing some of the stored wet season flows to address extremely low flows in the dry season, or to contribute to the volume and timing of reverse flows in the Tonle Sap Lake.

In general, while the development of storage over the last ten years has contributed to changing flow patterns, storing water in the wet season, and making it available in the dry season provides a shared benefit to the storage as well as opportunities for climate adaptation. It allows for the expansion of irrigation in the dry season, which would have otherwise not been possible, could contribute to environmental flows, provides additional flows for downstream mainstream hydropower, and can support sediment transport and environmental needs. This wet-to-dry season shift in flows must, nonetheless, consider the reasonable and equitable use of the shared waters from both socio-economic and environmental perspectives[25].

Nonetheless, the shoulder season at the start of the wet season is where the biggest impacts on the natural flow regime may occur under 'normal' drought conditions. The runoff from the first rains will almost certainly be stored, thus delaying the onset of the higher flows and hence the start of the return flows in the Tonle Sap Lake. This is an important ecological signal, driving much of the fisheries potential of the Lake. Active management of the mainstream flows could therefore aim at using the Tonle Sap Lake as a bellwether for drought management operations aimed at adjusting the timing and volume of the return flow as a drought mitigation measure. This, however, means diverting some of the flows away from the storage channel towards downstream flows at the start of the wet season. While some of this water could be used for mainstream power generation further downstream, this action will come at the risk of generation potential if the wet season rains fail. This, as we have seen from the previous section, is becoming increasingly likely.

Nonetheless, the measure, if supplemented by Nature-based Solutions applied as a medium-term measure, could provide relief for the people dependent on the lower Mekong mainstream during droughts.

4.3 Opportunities from a whole-basin perspective

Water resources management in the LMRB is closely tied to several other sectors, i.e., agriculture, power generation, fisheries potential, navigation, and environment. Together, these sectors form a complex interactive system with upstream, downstream, left bank and right bank, and tributary inflows. This is increasingly referred to as the Water-Energy-Food (WEF) nexus. This report suggests that the opportunities to address the challenges faced by the LMRB must take a whole basin and WEF nexus perspective. Possible directions for ongoing cooperation and studies are as follows:

4.3.1 Consensus on core issues

According to Elinor Ostrom, building knowledge and trust are essential for solving collective-action problems (Ostrom, 2011). It should, therefore, be acknowledged that developing a common and scientifically-based understanding of the status of the basin and key issues is the first step to building knowledge and mutual trust. This is also one of the purposes of this Joint Study.

Besides the changing patterns of hydrological conditions in the basin, there are also other important questions that need further study. For example, (1) A scientific, comprehensive, efficient management

[25] This does not account for the other impacts of the storage in terms of retention of sediments, loss of riverine habitats, and changed timing of the first flush events.

mechanism and system to support the sustainable development of water resources from a whole basin and nexus perspective; (2) The relationship between flood detention and discharge in the basin, and scientific flood and drought management strategy; and (3) Balancing the higher water demand of social-economic development and ecosystem water demand.

4.3.2 Improve the water infrastructure

For flood management

Flood management has three components (the '3-P')[26]:

- Flood prevention: This includes measures to get the rainfall to soak into the ground where it falls, and includes soil, water, wetlands, and forest conservation projects (enhanced natural infrastructure or nature-based solutions). This may also include small flood detention ponds, which could support small scale irrigation in dry periods, or the coordinated management of larger upstream storage.
- Flood protection: This includes the construction of dikes and bunds in more densely populated areas, flood proofing infrastructure, or diverting flood waters to areas that can be flooded with little economic impacts.
- Flood preparedness: This includes measures to provide early flood warning, and contingency plans providing for rescue, recovery, and rehabilitation for flood-affected people.

A comprehensive Integrated Flood Risk Management (IFRM) plan covers all three of these elements, and it is recommended to develop an IFRM strategy for the Basin.

For drought management

Droughts are becoming increasingly more frequent in the LMRB. As the peak of agricultural water demands in the basin occurs in the dry season, increasing storage already provides an inherent drought management measure. However, as is evident from this report, severe droughts and increasing storage can change the volume and pattern of both wet and dry season flows, with concomitant impacts on ecological functioning and fisheries. The delayed start of the monsoons, together with the increased storage, is also likely to impact the timing and volume of the return flows to the Tonle Sap Lake and the end of wet season water levels in the lake (and hence early dry season flows into the delta). This may require the development of basin-wide operational rules that share the regional economic burden of severe droughts across the WEF nexus. These must recognise the seasonal risks to energy production and mainstream flows.

4.3.3 Joint actions for non-structure measures

Hydro-meteorological forecasting and warning

As outlined above, flood forecasting and early warning is a fundamental part of integrated flood risk management. According to the WMO, an effective flood forecasting system contributes 10% to 15% of the total flood prevention benefits across the globe. With the modern development of science and technology, hydrological forecasting, including flood and drought, has been greatly improved. To further extend the forecasting period and accuracy of the hydrological process, high-accuracy rainfall forecasting is needed. Therefore, a combination and development of hydrological and meteorological

[26] As per the EU's Flood Directive.

forecasting technology is recommended, and a whole-basin flood and drought forecasting system will certainly aid in the endeavours of flood prevention and drought relief.

Joint operational management of storage

The contribution from the Lancang River to the annual volume decreases further downstream along the mainstream while the contributions from the tributaries in the Mekong portion of the basin are increasingly important further downstream. This is also affected by the spatial distribution of the rainfall across the whole basin. It is therefore important that options for operational management of storage consider the storage across the whole basin. In this regard, a better and timely notification would be a good start.

Furthermore, operational models must forecast the risks and benefits of managed releases from storage on the timing of the Tonle Sap Lake reverse flows, and the end of wet season water levels in the lake. The following observations can be drawn from this Phase 1 study:

1. Operations to address droughts and to advance the timing of the onset of the delayed higher flows is possible, ***but***
2. This must be based on minimising the risks to generation capacity or 'replacing' the lost generation through other means***. In this case,***
3. The decision to make supplementary flow releases must be based on a seasonal forecast for the wet season, as well as shorter-term rainfall forecasts during the wet season, ***finally***
4. It will be essential to include generation capacity in the Source model to support scenario modelling across the WEF nexus.

For example, if the wet season forecast in April/May suggests good rains over the coming months, *and if* the short-term forecasts show that this is likely to start in the upcoming two weeks, then supplementary releases from storage can be contemplated. However, the short and medium risks to generation capacity would have to be determined and deemed to be acceptable. Because the onset of the rains will vary across the LMRB, there may be opportunities to generate additional energy to cover the possible short-term deficits through a shared power pool. This analysis can be made on a rolling basis as the wet season unfolds, enabling a frequent revisit of the potential for supplementary releases.

A similar analysis will be possible during the dry season, where the decisions will be based on forecast inflows to storage, the generation needs for the dry season, and the availability of 'surplus' water (as already contemplated in the 1995 Mekong Agreement).

In the longer term, smaller generation facilities or energy conservation measures can be considered to fill in the energy gaps due to supplementary releases. These may be pumped storage or floating solar options. Non-infrastructural interventions, like energy demand management and shifting the regional economies towards more climate resilient livelihoods, could also be considered.

Releases made from upstream storage can provide additional benefits to minimise or mitigate the impacts of downstream hydropower infrastructure on the mainstream. The additional flows provided can support sediment pressure flushing operations of run-of-river hydropower projects, thus potentially improving sediment transport[27]. Additional generation capacity in these hydropower projects due to upstream supplementary releases may provide additional revenue for impact mitigation. The additional

[27] It is critically important to keep in mind the advantages and disadvantages of storage construction/operation. On the one hand, additional flows from the upstream storage could help improve sediment flushing of downstream storage when it is performed at the right amount/time. On the other hand, storage operation without proper management would increase the chance of sediment trapping and breaking of river connectivity.

flows on the tributary hydropower could potentially support hydropeaking operations, thus avoiding the need for hydropeaking on the mainstream. Supplementary flows may also provide additional water for fish passage facilities at the mainstream hydropower.

Done at the right time, these releases could help correct the timing of the first flush events and the start of the reverse flow into the Tonle Sap Lake, as well as to 'top up' the Tonle Sap Lake, thus benefiting flows into the delta at the start of the following dry season. However, this will require some additional scenario analyses for Phase 2 of the Joint Study and the development of a basin-wide operational model such as that being proposed by the MRC.

While the above operations appear feasible, they will have to be tested using a comprehensive basin-wide suite of models. These must include short- and medium-term (seasonal) forecasts based on forecast meteorological conditions. It is also essential to include the opportunity to simulate flexible operational rules at the larger hydropower, as well as flow/generation rule curves for these facilities. The hydropower operators will also need to share near real-time data on inflows, outflows (for generation and supplementary releases), water levels, active storage, and generation outputs.

This is a step up from the current plans to share hydrological data and may require commitments from the hydropower operators (in the whole basin) as well as, potentially, from the power purchasers.

5 CONCLUSIONS

5.1 Changes to the spatio-temporal distribution of streamflow

The streamflow of the LMR has exhibited significant changes from 1980 to 2020, with the year 2009 identified as the changing-point year. Notably, no significant hydrological changes were observed between 1980 and 2009. However, from 2010 to 2020, the annual flow of the LMR was found to be lower than that of 2000-2009, which can be attributed to drier climate conditions. Despite this, the seasonal pattern of LMR flows remains pronounced, with the dry season flows being amplified and the wet season flows reduced due to basin development. Moreover, when compared to 2000-2009, the daily, weekly minimum and monthly minimum flows for 2010-2020 at all mainstream stations show an increase, while the maximum flows exhibit a decrease.

The trend observed in the data indicates a shift in the timing of minimum daily flows over the past two decades. From 2000 to 2009, the minimum daily flow typically occurred in early April. However, from 2010 to 2020, the minimum daily flow shifted to mid-March. This change suggests a potential trend towards earlier minimum daily flows in recent years about three weeks. Furthermore, the average timing of maximum daily flows of the mainstream stations remains relatively the same (late August or early September).

The data shows a significant shift in the seasonal volume ratio at upstream stations, specifically at Jinghong and Chiang Saen, from 20% dry season volume over 80% wet season volume for the period 2000-2009 to 40% dry season volume over 60% wet season volume for the period 2010-2020. This suggests a substantial increase in the dry season volume and a decrease in the wet season volume at these stations.

On the other hand, downstream stations, such as Chiang Khan to Nong Khai/Vientiane, showed a smaller change in the seasonal volume ratio. It shifted from 20% dry season volume over 80% wet season volume for the period 2000-2009 to 30% dry season volume over 70% wet season volume for the period 2010-2020. Similarly, Nakhon Phanom/Thakhek to Stung Treng showed a shift from 15% dry season volume over 85% wet season volume for the period 2000-2009 to 20% dry season volume over 80% wet season volume for the period 2010-2020.

As the whole basin features lower precipitation in the latter period, furthermore, there was a decrease in the annual flow at Jinghong, amounting to -9 billion m^3 or a reduction of 17%. Similarly, the annual flow at Luang Prabang, Nong Khai/Vientiane, and Stung Treng experienced reductions of -2 billion m^3 (-2%), -17 billion m^3 (-12%), and -78 billion m^3 (-18%), respectively.

The analysis of flood patterns reveals that 2019 and 2020 were extreme hydrological drought years in the Lancang/Mekong mainstream, exceeding the two standard deviations. Additionally, several years in 2010-2020, particularly downstream, experienced significant hydrological droughts beyond one standard deviation. In contrast, the years from 2000-2009 saw deviations from the one standard due to higher flood volumes or severe flood years.

5.2 Changes in flood pulse of the Tonle Sap Lake

Overall, the accumulated volume and duration of the reverse flows during 2010–2020 have considerably reduced when compared to 2000–2009. This is associated with both reduced wet season rainfall (which reduced the flows in the lower Mekong mainstream) and increased storage and water withdrawal in the whole basin. Thus, the combined impacts have reduced the flows from the lake to the Delta at the onset of the dry season.

During 2010–2020, the total volume and duration of the reverse flows to the Tonle Sap Lake have considerably decreased. This points toward recent meteorological drought conditions of 2016 and 2019–2020 as one of the main causes of the changes. A more detailed examination of the factors influencing alterations in the flow of the Tonle Sap Lake will be undertaken in the subsequent phase of the study.

5.3 What contributes to changes of hydrological conditions in the basins?

Two key factors contribute to hydrological changes in the LMRB: natural factors, including precipitation patterns, evaporation rates, soil properties, topography, and human activities such as infrastructure development, water management and land cover and land use changes. These two factors interact and influence the amount, timing, and water distribution within the Basin.

For this study, the natural factors considered are the meteorological/hydrological drought using the SPI, SPEI, and SRI:

- **Long-term trend**: Generally, the dry and wet seasons show trends toward more severe droughts over large areas of the LMRB. Furthermore, the period of 1950–2021 shows considerable spatial changes in both these indexes when compared to 120-year data (1901–2021). This suggests that the trend towards 'drier' conditions is more recent and is likely to be related to the changing climate.
- **Frequency:** The trend is for significant increases in drought frequency over large areas of the LMRB during the last 20 years. This was particularly evident in the exceptional drought category for the lower Lancang and upper Mekong regions. A great degree of consistency of the drought frequency distribution of SPIs estimated from various meteorological datasets (CRU TS, ERA5-Land, and CHIRPS) reveals that the LMRB has been exposed to more frequent meteorological droughts in 2010–2020.
- **Duration:** Trends in droughts duration are for longer droughts over large areas of the basin. Severe and exceptional droughts were also prolonged in many parts of the basin, and the exceptional drought was significantly prolonged in the middle part of the whole basin.
- **Intensity:** The overall trend in drought intensity is for the mild droughts to become less severe, whereas there is a slight intensifying in the severity of the exceptional droughts over most of the basin and significant change for small patches in the lower Lancang section.
- **Role of the El Niño phenomenon:** There is considerable evidence that meteorological droughts in the LMRB are driven by the presence of an El Niño event and that the intensity of the event is a good indicator of the intensity of the meteorological drought over the Basin. Forecasts of the El Niño events will therefore be a good indicator of the potential drought.

From the above analysis of long terms trend, frequency, duration, intensity and role of the El Niño, it is concluded that climate change shows significant impact in the basin.

Frequency changes in meteorological droughts (SPI by CHIRPS) and areal hydrological conditions (SRI by VIC model) drought frequency changes between 2000–2009 and 2010–2020, have revealed a **remarkable similarity in drought frequency changes of the meteorological and hydrological droughts** over the Mekong River Basin. The frequency of both meteorological and hydrological droughts increased intensively during 2010–2020 compared to 2000–2009. Moderate and severe droughts have the most significant frequency spatially. The results also indicate that meteorological factors play a dominant role in hydrological processes and changes.

5.4 What caused the differences in the 2000–2009 and 2010–2020 flows?

The separation between the periods 2000–2009 and 2010–2020 is basing on available dataset. It was observed that the annual flow of the LMR during the 2010–2020 period was lower compared to the 2000–2009 period, likely due to drier climate conditions. Additionally, the impact of basin development is evident in the seasonal flow patterns, with amplified dry season flows and reduced wet season flows in the latter period.

Irrigation is the most prominent consumptive water use in the Mekong River Basin, and the area under irrigation has also gradually expanded over the last 20 years. Total water withdrawal in the basin was estimated at 62 billion m^3, or 13% of the river's average annual discharge, and irrigation withdrawal accounts for 56 billion m^3 or 91% of the total in 2012. Total water withdrawal in the Lancang River basin is 2.8 billion m^3 in 2020, a small portion of the total water withdrawal of the whole basin. Though consuming large amounts of water, due to gradual changes, irrigation is not expected to contribute substantially to the hydrological changes between the two periods. There may be some reduction of flows due to irrigation in the dry season, and recent increases in irrigation (together with sand mining) in the basin may have played some role in increasing the potential for saline intrusion. Similarly, while there have been remarkable increases in the diversion of flow for domestic and industrial uses, this is comparatively smaller fraction of the flows on the mainstream. But it is noticeable that the rapidly growing population and economy in the Mekong delta may generate unprecedented demand of water from the Mekong. It is needed to share more information and data on tidal changes, water and land use, and ground water level in the past 60 years or even longer for scientific research.

Although increased hydropower storage capacity in the whole basin does not consume much water, it does contribute to the changes in hydrological conditions, in particular extreme flow in the wet and dry seasons.

The simulated results from the THREW and SWAT/Source models provide consistent trends of the hydrological impacts of the water resource development and climate. The two model packages demonstrate that the development of water storage has increased the low water levels in the dry season and decreased the high flow in the wet season in the whole basin. This is more evident at upstream stations but less evident further downstream, where the contributions from the portions of the tributaries are greater.

5.5 Opportunities for adaptive management

While all six riparian states' foreign policies are founded on respect for sovereignty, the key challenges for the Lancang-Mekong River are transboundary and requires joint actions to support the reasonable and equitable use of the shared water and avoidance of significant transboundary harm. This is evidenced by occasions where supplementary releases have been made to mitigate the impacts of the droughts and extreme low flows in the Mekong mainstream reach, thanks to the political commitment of the six basin countries to enhancing joint efforts to address basin-wide flood and drought with the commencing of the LMC/MLC mechanism, together with the MRC cooperation. Similarly, the MOU signed between the LMC Water Center and MRC and this present Joint Study also underpin the growing recognition that increased cooperation is needed.

In general, increasing storage can provide opportunities for regional climate adaptation. Supplementary releases from storage can be used to mitigate the impacts of severe droughts (i.e., 2016), and if well coordinated among the riparian countries in operation and management of the storage, can mitigate the impact of storage on the flood, sediment trapping and fisheries. This may also provide the opportunity to adjust the timing and volume of the return flows to the Tonle Sap Lake.

Supplementary releases, however, pose short- and medium-term risks and additional costs to generation capacity. These will need to be quantified and accepted by all parties. This means including electricity generation capacity in a basin-wide operational model. It will also require short-term (up to 2 weeks) and medium-term (seasonal) forecasts to be included in the models. The risks across the WEF nexus can then be analysed on a rolling basis as the wet season unfolds, enabling a frequent revisit of the potential for supplementary releases. It should be pointed out that supplementary releases may need to be institutionalised only through consultation and negotiation in order to make it workable in the long run if such releases are considered necessary by all parties involved. There are a few cases in other parts of the world that could shed some light on such arrangements.

In the longer term, smaller generation facilities or energy conservation measures can be considered to fill in the 'energy generation gaps' due to supplementary releases. These options may include pumped storage or floating solar options. Additional storage operated primarily for flow compensation can also be considered. Non-infrastructural interventions should also be considered as medium to longer-term strategies, like energy demand management, water conservation in all sectors, natural-based solutions (e.g. preservation of existing natural storage on wetlands and floodplains) and shifting the regional economies towards more climate-resilient livelihoods.

6 LIMITATION OF THE JOINT STUDY PHASE 1

The Joint Study Phase 1 has enhanced comprehension for the first time among the six riparian countries of the Lancang-Mekong of the alterations in hydrological patterns resulting from climate change and water infrastructure development. There is a common understanding on the changes in annual, seasonable and monthly flows. The current findings indicate that hydrological changes stem from two primary drivers: (1) natural elements such as patterns of precipitation and evaporation, soil characteristics and landform; and (2) human activities encompassing water infrastructure development and operation, water management, and changes in land cover and land use. These factors interact and influence the quantity, timing, and distribution of water within the Basin.

Although extensive efforts were undertaken to gather and analyse data and calibrate the models during the Joint Study Phase 1, more time, data and analysis are needed to clearly differentiate between the impacts caused by climate change and human activities. This will be taken up during Phase 2.

6.1 Data

These limitations of data availability highlight the challenges and gaps in data quality, which should be considered when interpreting the findings and conclusions of the Study.

- There is some uncertainty surrounding **discharge measurements and derived rating curves** for some stations. This limitation implies that the accuracy of the data collected may still have some level of uncertainty.
- **Historical hydrometeorological data and information**, i.e. rainfall, temperature, water level, discharge, etc., are included in the Study. However, the availability or completeness of the historical data could affect the comprehensive analysis of past trends and patterns.
- The Study includes **reservoir characteristics, general operating rules, filling, storage levels, and inflow/outflow** data. Nevertheless, accessing complete and up-to-date information on reservoir operations could improve the analysis's accuracy.
- The Study considers the status of **irrigation** (i.e. crop area, type, calendar and the source of irrigation water). However, additional data on irrigation activities (particularly the extensive use of groundwater) is needed to capture the current and future conditions in the basin. This data will contribute to a more accurate representation of the current and future state of the models.
- Data on **domestic/industrial water supply**, including the most recent updated population figures, consumption rates, etc., are considered in the Study. However, the availability and accuracy of this data have limitations, which could impact the assessment of water demand and its implications on the hydrological system.
- The Study aims to analyse **variations in water level and discharge in the Delta region** over an extended period. However, the non-availability of the data for a long period (e.g. from the 1960s) hampers the analysis's comprehensiveness.

6.2 Models

The Study recognises certain limitations in the modelling aspect, which indicate areas that require further enhancements and refinements to improve the accuracy and comprehensiveness of the modelling framework.

- The assumptions and integration between hydrological processes (SWAT) and water system modelling (Source) need additional evaluation and testing. This suggests that **complete integration of these components in the Source Modelling Platform** could accomplish more accurate modelling outcomes.
- The modelling estimates of consumptive **water use for irrigation schemes and domestic/industrial water demands** could benefit from more extensive data collection. The current models may not offer precise estimations of water consumption, which could potentially impact the analysis of water availability and demand.
- The **land use (land cover) and soil data** used in the hydrological models (both THREW and SWAT) should be updated. The reliance on dated or incomplete land use and soil data may introduce limitations and uncertainties in the modelling results.
- The **groundwater component** in the models is simplified, indicating that the models may not fully capture the complexities of groundwater dynamics. This limitation could affect the analysis of the interaction between surface water and groundwater.
- The models have limitations in capturing certain **details of the hydrological cycle**. This implies that some aspects of the hydrological processes may not be fully represented or accounted for, potentially leading to less accurate modelling results.
- The development and integration of the Source model with **power generation, sediment transport, and ecological models** are necessary. These aspects are currently not fully integrated, which may affect the comprehensive understanding of the interactions between these components and their influence on the hydrological system.

6.3 Results

For detecting variations in hydrological patterns and distinguishing between the influences of climate change and human activities, further efforts should be devoted to data collection, model improvement, and the exploration of new methods in the Joint Study Phase 2 and beyond.

Due to the above limitations of available data and the modelling approach employed, the Study's results primarily focus on average monthly and seasonal flow rather than daily and sub-daily water level variations. This highlights the need for additional data and refined modelling techniques to capture finer-scale temporal variations in water level fluctuations for a more comprehensive understanding of the system dynamics.

6.4 Way forward for the Joint Study Phase 2

To address these limitations, Phase 2 of the Joint Study will focus on implementing the following approaches:

- Further investigation into the short-term water level fluctuations will aim to enhance the understanding of this aspect.
- Engagements with stakeholders will be conducted to formulate more comprehensive scenarios for testing purposes and to ensure a thorough examination of various potential scenarios.
- The models in the Joint Study Phase 1 will be revisited, emphasising the calibration and validation processes based on newly acquired additional data. This will contribute to refining the accuracy and reliability of the models.

- The possibility of quantifying the extent of changes in hydrological conditions for key sites/stations will be explored, enabling a more nuanced understanding of the system's behaviour.
- Additional key hydrological stations may be included in the next phase, expanding the coverage and depth of the Study to capture a broader representation of the hydrological system and to quantitatively differentiate the impacts caused by climate change and human activities.

7 RECOMMENDATIONS

While Phase 1 of the Joint Study has made important advances in our joint understanding of the changing hydrological patterns of the Lancang-Mekong River Basin, there are still some issues that must be addressed. Recommendations for further work are as follows:

Short-term

- **Enhanced data and information sharing**. As global climate change and the associated droughts and floods will play an increasingly important role in driving the basin's hydrological conditions, it is critical for basin countries to share more information on meteorological flow conditions. This should be expanded to include the tributaries. Near real-time sharing of storage levels and hydropower operations will also be critical to support operational models and adaptive management of the basin. More information and data on tidal changes, water and land use, and groundwater level in the past 40 years or even longer in the Mekong Delta is also critical for scientific research with a basin-wide perspective. The information sharing platform proposed under the LMC cooperation framework provides an unprecedented opportunity to support this process. It is encouraged to explore and improve the better and more effective notification of storage releases and restrictions, and both LMC and MRC are ideal mechanisms to enhance notification of unusual releases and restrictions.

Medium-term

- **Coordinated management of water resources**. It is recommended that riparian countries jointly formulate action plans and strategies for coordinated water resource management. The LMC water cooperation's Five-year Action Plan (2023–2027), which is currently being formulated, and the MRC's Basin Development Strategy (2021–2030) and the associated adaptive management plan provide the opportunity to advance this.
- **Comprehensive drought and flood management strategy**. Climate change driven floods and droughts will play an increasingly significant impact on regional development. Both structural and non-structural measures will be needed to mitigate these impacts. It is recommended that a comprehensive Flood and Drought Risk Management Strategy is formulated based on the prevention, protection, and preparedness (3-P) principles.
- **More Joint Studies**. Phase 1 of this current joint study lays a solid foundation and highlights the benefits of combining the skills and experience from all the riparian countries. It has highlighted that joint studies can support the realisation of the 2030 SDGs. However, there are many issues that remain unclear. It is critical that coordinated water resources management and the flood and drought strategies proposed above are based on a common understanding of the challenges and sound science, including sediment movement/transport, salinity intrusion, ecological conservation, recovery of reverse flow of the Tonle Sap Lake, etc. It is therefore proposed that additional joint studies are undertaken to support these processes.
- **More capacity building plan**. Coordinated operational management, integrated flood and drought management strategies and water governance should be based on sound science and a common understanding of the LMRB. There is consequently a need for educated water and related policy makers, managers, engineers and scientists. It is therefore recommended that a capacity building strategy is formulated that addresses the knowledge, understanding and capacity gaps. This should include all aspects of water resources management and include formal (post-graduate and diploma) courses as well as informal training courses.

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ANNEX A – IDENTIFICATION OF BREAK YEAR OF ABRUPT CHANGES IN HYDROLOGICAL PATTERN

A.1 The Pettitt test for abrupt changes in hydrological pattern

The Pettitt test (1979) is a useful tool for detecting abrupt changes in hydrological or meteorological elements. It allows us to determine the presence of abrupt change points, identify the timing of these changes, and assess their significance. This method is known for its convenience in application, computational robustness, and ability to handle outliers without interruption. It is a reliable approach for analyzing data with abrupt changes and can provide valuable insights in hydrological or meteorological studies.

For hydrological or meteorological element $X = (x_1, \ldots, x_n)$, let's assume that its abrupt change point is x_t, where X is divided into two parts $(x_1, x_2, \ldots, x_t)$ and $(x_{t+1}, x_{t+2}, \ldots, x_n)$, where t being the potential abrupt time. The test statistic $U_{t,n}$ is defined as:

$$U_{t,n} = U_{t-1,n} + \sum_{j=1}^{n} sgn(x_t - x_j) \qquad t = 2, \ldots, n$$

Where $sgn(\cdot)$ is a symbolic function, which is defined as follows,

$$sgn(x_j - x_k) = \begin{cases} 1 & (x_j - x_k) > 0 \\ 0 & (x_j - x_k) = 0 \\ -1 & (x_j - x_k) < 0 \end{cases}$$

The statistic K_t is defined to identify the abrupt time point:

$$K_t = \max_{1 \le t \le n} |U_{t,n}|$$

After finding the abrupt time point, its significance level P_t is calculated by the following equation:

$$P_t \approx 2exp\,(\frac{-6{K_t}^2}{n^3 + n^2})$$

For the given confidence level α, if $P_t < \alpha$, there is the significant abrupt at t; Otherwise, there is no significant abrupt at t.

The Pettitt test was conducted on the annual average discharge at Chiang Sean station for the period of 1980 to 2020, and the results are presented in **Figure A-1** and **Figure A-2**. In **Figure A-1**, the black line represents the multi-year annual average discharge, while the red and blue lines show the average discharge before and after the abrupt change year, respectively, denoted by the green line. **Figure A-2** displays the multi-year Pettitt test value obtained based on the annual discharge, shown as the black line. According to the Pettitt test, the abrupt change year for the annual average discharge at Chiang Sean is identified as 2009. The figures visually depict the abrupt change in discharge patterns and provide important insights for further analysis.

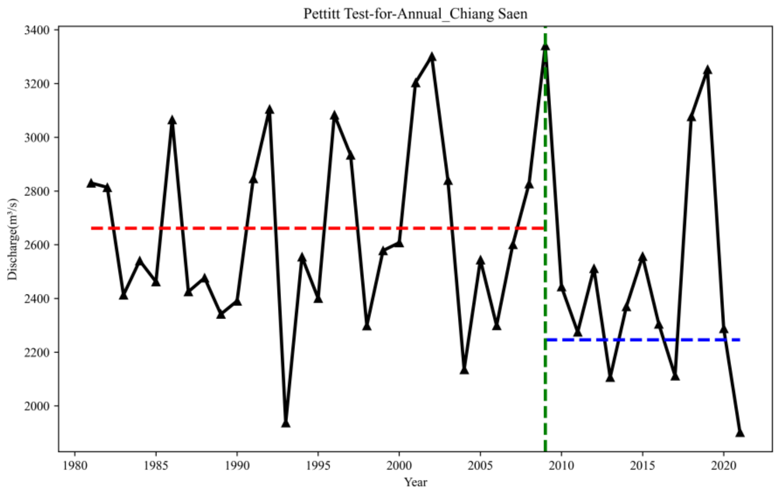

Figure A-1. Pettitt test for annual discharge in Chiang Sean station from 1980 to 2020 shown in discharge

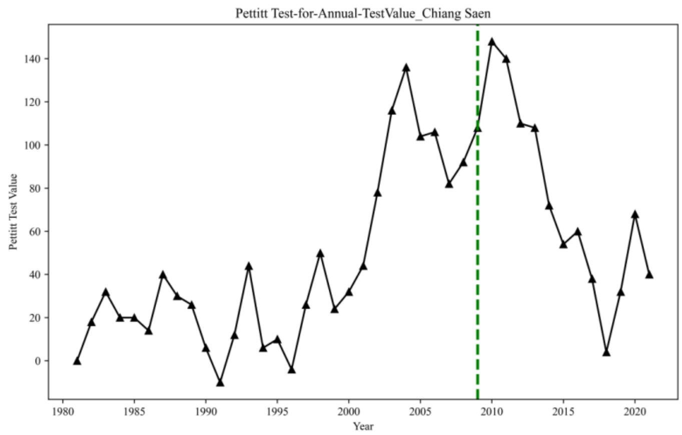

Figure A-2. Pettitt test for annual average discharge in Chiang Sean from 1980 to 2020 shown in Pettitt test value

A.2 Analysis of monthly discharge for 1985-2009 and 2000-2009

With identification of the break year of 2009, a comparative analysis to examine the differences of monthly discharge for 1985-2009 and 2000-2009 were performed at all stations along the Mekong mainstream. The results suggest that only minor differences were found at most of the stations as indicated in **Figure A-3**. Hence, the study adopted two sub-periods: (1) 2000 to 2009, and (2) 2010 to 2020.

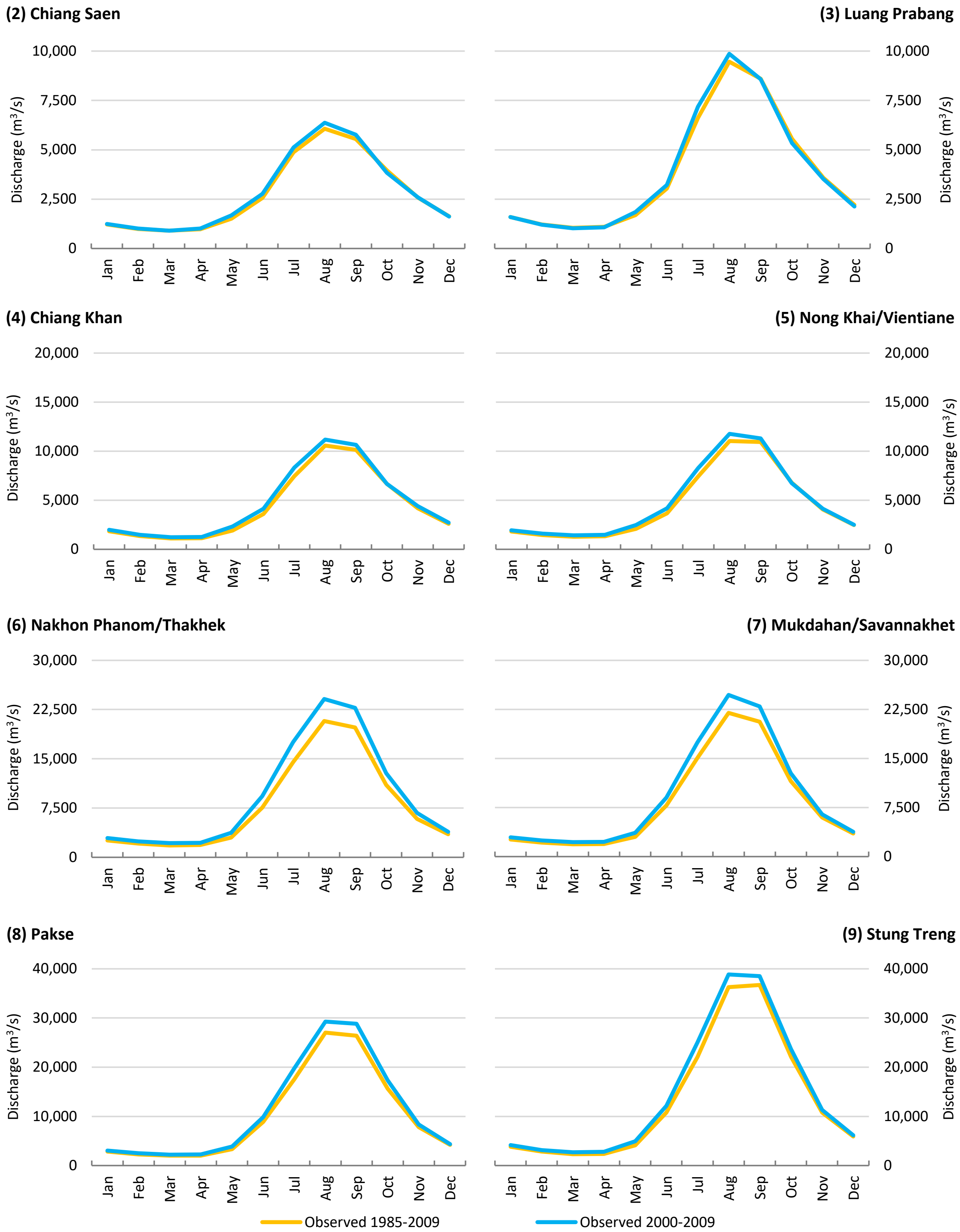

Figure A-3. A comparative analysis of monthly discharge for 1985–2009 and 2000–2009

A.3 Reference of Annex A

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ANNEX B – DATA SHARING FROM LMC WATER CENTER

Table B-1. Precipitation data in the Lancang River Basin

No	Station Code	Station Name	Latitude	Longitude	Interval	Data start	Data end
1	56018	–	32.53	95.17	Daily	1961	2020
2	56125	–	32.12	96.28	Daily	1961	2020
3	56128	–	31.22	96.60	Daily	1991	2012
4	56137	–	31.09	97.10	Daily	1961	2020
5	56444	–	28.48	98.92	Daily	1991	2012
6	56548	–	27.10	99.17	Daily	1961	2020
7	56751	–	25.42	100.11	Daily	1961	2006
8	56856	–	24.28	100.52	Daily	1961	2020
9	56946	–	23.33	99.24	Daily	1990	2006
10	56950	–	22.28	99.48	Daily	2006	2017
11	56951	–	23.53	100.05	Daily	1961	2020
12	56954	–	22.34	99.56	Daily	1961	2020
13	56959	–	22.00	100.78	Daily	1991	2017
14	56964	–	22.47	100.58	Daily	1961	2020
15	56969	–	21.28	101.35	Daily	1961	2020
16	56977	–	22.35	101.51	Daily	1961	2020

Table B-2. Temperature data in the Lancang River Basin

No	Station Code	Station Name	Latitude	Longitude	Interval	Data Start	Data End
1	56018	–	32.53	95.17	Daily	1991	2020
2	56125	–	32.12	96.28	Daily	1991	2020
3	56128	–	31.22	96.60	Daily	1991	2012
4	56137	–	31.09	97.10	Daily	1991	2020
5	56444	–	28.48	98.92	Daily	1991	2012
6	56548	–	27.10	99.17	Daily	1991	2020
7	56751	–	25.42	100.11	Daily	1991	2012
8	56856	–	24.28	100.52	Daily	2006	2020
9	56946	–	23.33	99.24	Daily	1991	2012
10	56950	–	23.28	99.48	Daily	2006	2017
11	56951	–	23.53	100.05	Daily	2006	2020
12	56954	–	22.34	99.56	Daily	1991	2020
13	56959	–	22.00	100.78	Daily	1991	2017
14	56964	–	22.47	100.58	Daily	1991	2020
15	56969	–	21.28	101.35	Daily	1991	2020
16	56977	–	22.35	101.51	Daily	2006	2020

Table B-3. Characteristics of reservoir on the Lancang River

No	Dam name	Com. year	Installed capacity	Annual energy	Dam Height	Full level	Dead level	Full storage	Dead storage	Active storage
		–	(MW)	(GWh)	(m)	(mamsl)	(mamsl)	(mil. m^3)	(mil. m^3)	(mil. m^3)
1	Jinghong	2009	1,750	5,570	108	602	595	1,140	810	249
2	Nuozhadu	2014	5,850	23,912	262	807	756	23,703	10,414	12,300
3	Dachaoshan	2003	1,350	5,500	115	906	860	890	465	367
4	Manwan	1995	1,670	6,710	132	994	982	920	630	257
5	Xiaowan	2010	4,200	18,990	292	1,236	1,162	14,560	4,750	9,900
6	Gongouqiao	2012	900	4,041	105	1,319	1,311	316	196	120
7	Miaowei	2017	1,400	5,999	140	1,408	1,373	660	359	301
8	Dahuaqiao	2018	920	4,070	106	1,477	1,466	293	252	41
9	Huangdeng	2018	1,900	8,578	203	1,619	1,604	1,613	1,031	582
10	Tuaba	2023	1,400	6,360	158	1,735	1,725	1,039	735	304
11	Lidi	2019	420	1,753	74	1,818	1,813	75	57	18
12	Wunonglong	2019	990	4,116	138	1,906	1,894	284	236	48

ANNEX C – DATA SHARING FROM MRC

Table C-1. Discharge data in the Mekong River

No	River	Station Name	Period
1	Mekong	Chiang Saen	2017–2022
2	Mekong	Chiang Khan	1985–2022
3	Mekong	Nong Khai	2017–2022
4	Mekong	Mukdahan	2017–2022
5	Mekong	Khong Chiam	2017–2022
6	Mekong	Pakse and	2017–2022
7	Mekong	Stung Treng	2017–2022

Table C-2. Minimum and maximum temperature data for 2017–2022 in the Mekong River Basin

No	Station Code	Station Name	Latitude	Longitude
1	130305	Battambang	13.10	103.20
2	100401	Kampot	10.60	104.19
3	120504	Kampong Cham	12.00	105.45
4	120603	Kratie	12.49	106.02
5	110425	Pochentong	11.55	104.92
6	130306	Siem Reap	13.37	103.85
7	130501	Stung Treng	13.52	105.97
8	190202	Luang Prabang	19.88	102.13
9	150504	Pakse	15.12	105.78
10	160405	Savannkhet	16.55	104.75
11	190103	Sayaboury	19.20	101.73
12	160502	Seno	16.67	105.00
13	170404	Thakhek	17.42	104.80
14	170203	Vientiane	17.95	102.57
15	90503	Ca Mau	9.17	105.13
16	100509	Can Tho	10.05	105.79
17	100505	Chau Doc	10.70	105.12
18	100511	Moc Hoa	10.22	106.35
19	100504	Rach Gia	10.00	105.08

Table C-3. Precipitation data for 1980–2020 in the Mekong River Basin

No	Country	MRC Code	Station Name	Latitude	Longitude
1	Cambodia	130305	Battambang	13.10	103.20
2	Cambodia	110433	Oral	11.69	104.14
3	Cambodia	130321	Prasat Bakong	13.36	103.99
4	Cambodia	120302	Pursat	12.55	103.90
5	Cambodia	110303	Koh Kong (Ville)	11.63	103.00
6	Cambodia	130320	Angkor Chum	13.69	103.66
7	Cambodia	100303	Sihanouk Ville	10.62	103.48
8	Cambodia	110512	Kamchay Mea	11.57	105.67
9	Cambodia	120518	Taing Krasaing	12.57	105.06
10	Cambodia	120402	Staung	12.95	104.57
11	Cambodia	110503	Svay Rieng	11.08	105.78
12	Cambodia	110511	Prek Tameak	11.75	105.03
13	Cambodia	120503	Baray	12.40	105.09
14	Cambodia	120516	Prasat Sambo	12.89	105.08
15	Cambodia	120303	Maung Russey	12.77	103.45
16	Cambodia	120427	Tpaung	11.75	104.44
17	Cambodia	110425	Pochentong	11.55	104.92
18	Cambodia	100419	Angkor Borey	10.99	104.98
19	Cambodia	120425	Prey Prous	12.80	104.83
20	Cambodia	120504	Kompong Cham	12.00	105.45
21	Cambodia	130325	Siem Reap	13.37	103.85
22	Cambodia	110514	Prey Veng	11.48	105.33
23	Cambodia	120404	Kompong Thom	12.69	104.90
24	Cambodia	120312	Kravanh	12.68	103.65
25	Cambodia	110409	Takhmao	11.44	104.95
26	Cambodia	120603	Kratie	12.49	106.02
27	Cambodia	130501	Stung Treng	13.52	105.97
28	Cambodia	120401	Kompong Chhnang	12.24	104.67
29	Cambodia	120417	Ponley	12.44	104.47
30	Cambodia	110432	Kong Pisey	11.30	104.63

No	Country	MRC Code	Station Name	Latitude	Longitude
31	Cambodia	110431	Baset	11.15	104.54
32	Cambodia	110413	Phnom Srouch	11.38	104.38
33	Lao PDR	140705	Attapeu	14.47	106.83
34	Lao PDR	160504	Ban Donghen	16.00	105.78
35	Lao PDR	180205	Ban Hinheup	18.63	102.33
36	Lao PDR	160505	Ban Kengkok	16.43	105.20
37	Lao PDR	170505	Ban Kouanpho	17.48	105.42
38	Lao PDR	150506	Khongsedone	15.57	105.80
39	Lao PDR	150604	Laongam	15.47	106.17
40	Lao PDR	190202	Luang Prabang	19.88	102.13
41	Lao PDR	170502	Muong Mahaxay	17.41	105.20
42	Lao PDR	180307	Muong Kao (Borikhane)	18.57	103.73
43	Lao PDR	180308	Muong May	18.50	103.67
44	Lao PDR	140501	Muong Khong	14.12	105.83
45	Lao PDR	200201	Muong Ngoy	20.57	102.60
46	Lao PDR	160605	Muong Phine	16.52	106.05
47	Lao PDR	160601	Muong Sepon	16.03	106.23
48	Lao PDR	150607	Nikhom km34	15.18	106.43
49	Lao PDR	200204	Oudomxay	20.68	102.00
50	Lao PDR	190203	Pak Ka Nhoung	18.53	102.43
51	Lao PDR	180101	Paklay	18.20	101.40
52	Lao PDR	180303	Paksane	18.40	103.63
53	Lao PDR	150504	Pakse	15.12	105.78
54	Lao PDR	140505	Pathoumphone	14.77	105.97
55	Lao PDR	160506	Phalane	16.70	106.23
56	Lao PDR	150602	Saravan	15.72	106.43
57	Lao PDR	160406	Savannakhet	16.55	104.75
58	Lao PDR	150609	Sekong	15.08	106.85
59	Lao PDR	150508	Selabam	15.38	105.82
60	Lao PDR	160502	Seno	16.67	105.00
61	Lao PDR	190108	Thadeua (Sayaboury)	19.43	101.83
62	Lao PDR	170404	Thakhek	17.42	104.80

No	Country	MRC Code	Station Name	Latitude	Longitude
63	Lao PDR	180207	Vangvieng	18.93	102.45
64	Lao PDR	170203	Vientiane	17.95	102.57
65	Lao PDR	190302	Xiengkhouang	19.33	103.37
66	Thailand	013801	Khong Chiam	15.32	105.49
67	Thailand	013402	Mukdahan	16.58	104.73
68	Thailand	150101	Wang Saphung	17.30	101.78
69	Thailand	012001	Nong Khai	17.88	102.73
70	Thailand	013101	Nakhon Phanom	17.43	104.77
71	Thailand	170105	Chiang Khan	17.90	101.67
72	Thailand	199907	Chiang Rai	19.92	99.83
73	Thailand	200002	Chiang Saen	20.27	100.10
74	Viet Nam	120805	Buon Ho	12.92	108.27
75	Viet Nam	100504	Rach Gia	10.00	105.08
76	Viet Nam	039803	Can Tho	10.05	105.79
77	Viet Nam	120801	Buon Me Thuot	12.60	108.08
78	Viet Nam	160705	ALuoi	16.22	107.28
79	Viet Nam	160704	Hue	16.43	107.58
80	Viet Nam	120806	Mdrak	12.73	108.75
81	Viet Nam	170602	Dong Hoi	17.48	106.60
82	Viet Nam	140703	Pleiku	14.02	107.90
83	Viet Nam	160706	Dong Ha	16.85	107.08
84	Viet Nam	140715	Dak To	14.65	107.83
85	Viet Nam	170603	Tuyen Hoa	17.88	106.02
86	Viet Nam	180505	Huong Khe	18.18	105.70
87	Viet Nam	180504	Ha Tinh	18.35	105.90
88	Viet Nam	130803	An Khe	13.95	108.65
89	Viet Nam	090503	Ca Mau	9.17	105.13

ANNEX D – TSINGHUA HYDROLOGICAL MODEL BASED ON REPRESENTATIVE ELEMENTARY WATERSHED (THREW)

D.1 Description of the THREW model

The THREW model was an abbreviation of the Tsinghua Hydrological Model based on the Representative Elementary Watershed approach, which Prof. Fuqiang Tian's research team has developed at Tsinghua University. The model has been applied to about 50 small-, medium-, and large-sized watersheds around the world, such as the Ganges River basin, Nile River basin, Yangtze River basin, Chaobai River basin, and so on.

The THREW model discretises a given basin into representative elementary watersheds (REWs). Each of the REW is further divided into eight sub-zones, i.e., snow-covered zone (n-zone), saturated zone (s-zone), unsaturated zone (u-zone), vegetable covered zone (v-zone), bared zone (b-zone), sub-stream network zone (t-zone), glacier-covered zone (g-zone) and main channel reach zone (r-zone), as depicted in **Figure D-1**. Vegetation, snow, soil ice, and glacier ice are added to the existing system (water, gas, and soil matrix). As a result, energy-related processes (evaporation/transpiration occurring from various kinds of land cover and hydrological phenomena especially related to the cold region, such as accumulation and depletion of snowpack and glacier, and freezing and thawing of the soil ice) can be modeled in a physically reasonable way.

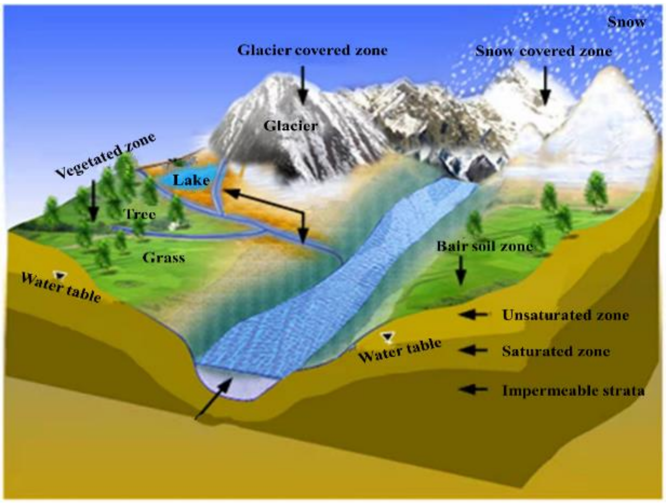


Figure D-1. Zones of REW in THREW model (Tian et al., 2006)

The REWs and zones are linked by a set of balance equations for mass, momentum, energy and entropy, formulated more systematically and extensible way. First, it derives the general form of time-averaged conservation laws of mass, momentum, energy, and entropy at the spatial scale of REW, independent of any zone and phase. After a series of assumptions aimed at watershed hydrological modelling, the interfaces, which determine the exchange terms arising in the balance equations, are simplified. The general form of conservation laws is then applied to derive the balance equations for each phase in each zone. For a watershed with M discrete REWs, a system of M×24 coupled equations is formed. All the balance equations are coupled together and solved simultaneously for either temperate or cold regions.

Besides rainfall-runoff processes, the important processes of glacier and snow melting, were incorporated into the model to make it applicable to cold regions.

Table D-1 lists the balance equations for cold regions, including those for the g-zone, n-zone, and u-zone. Mass and energy exchange terms among different zones are illustrated generally in **Figure D-2**.

Table D-1. Balance equations for glacier, snow, and unsaturated zone in THREW (Tian et al., 2006)

No.	Zone	Note	Balance equation
1		Liquid phase, mass balance	$0=e_l^{gT}+e_l^{gu}+e_l^{gt}+e_{lg}^{g}+e_{li}^{g}$
2	g-zone	Solid phase, mass balance	$\frac{d}{dt}(\overline{\rho_i^g} y^g \omega^g)=e_i^{gT}+e_{ig}^{g}+e_{il}^{g}$
3		Heat balance	$y^g \omega^g c^g \frac{d}{dt}\overline{T^g}=l'_{lg}(e_{lg}^{g}+e_{ig}^{g})+l_{il}e_{il}^{g}+\overline{R_n^g}\omega^g+Q^{gT}$
4		Liquid phase, mass balance	$\frac{d}{dt}(\overline{\rho_l^n}\varepsilon_l^n y^n \omega^n)=e_l^{nT}+e_l^{nu}+e_l^{nt}+e_{lg}^{n}+e_{ln}^{n}$
5	n-zone	Solid phase, mass balance	$\frac{d}{dt}(\overline{\rho_n^n}\varepsilon_n^n y^n \omega^n)=e_n^{nT}+e_{ng}^{n}+e_{nl}^{n}$
6		Heat balance	$y^n \omega^n c^n \frac{d}{dt}\overline{T^n}=l'_{lg}(e_{lg}^{n}+e_{ng}^{n})+l_{il}e_{nl}^{n}+\overline{R_n^n}\omega^n+Q^{nT}+Q^{nu}$
7		Liquid phase, mass balance	$\frac{d}{dt}\left(\overline{\rho_l^u}\varepsilon_l^u y^u \omega^u\right)=e_l^{uEXT}+\sum_{L=1}^{N_K} e_l^{uL}+e_l^{us}+e_l^{ub}+e_l^{uv}+e_l^{un}+e_l^{ug}+e_{li}^{u}$
8	u-zone	Solid phase, mass balance	$\frac{d}{dt}\left(\overline{\rho_i^u}\varepsilon_i^u y^u \omega^u\right)=e_{il}^{u}=-e_{li}^{u}$
9		Simplified mass balance	$\rho_l y^u \omega^u \frac{d}{dt}\left(\varepsilon_l^u\right)=e_l^{ub}+e_l^{uv}+e_l^{un}+e_l^{ut}-\rho_i y^u \omega^u \frac{d}{dt}\left(\varepsilon_i^u\right)$
10		Heat balance	$\omega^u y^u c^u \frac{d}{dt}\overline{T^u}=Q^{ub}+Q^{uv}+Q^{un}+Q^{ut}+l_{il}\rho_i y^u \omega^u \frac{d}{dt}\left(\varepsilon_i^u\right)$

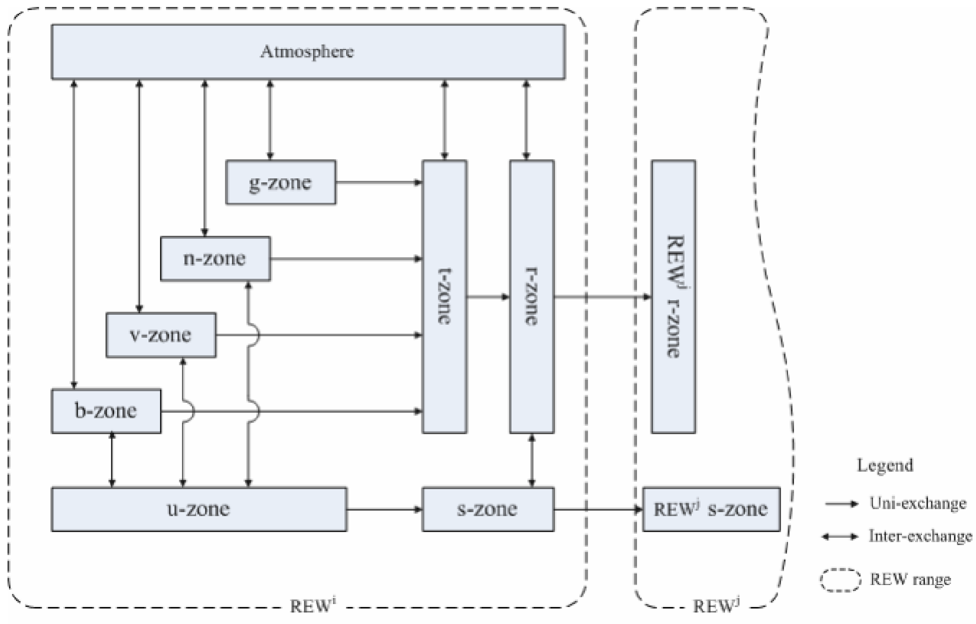


Figure D-2. A general description of mass/energy exchange terms among zones in cold regions (Tian et al., 2006)

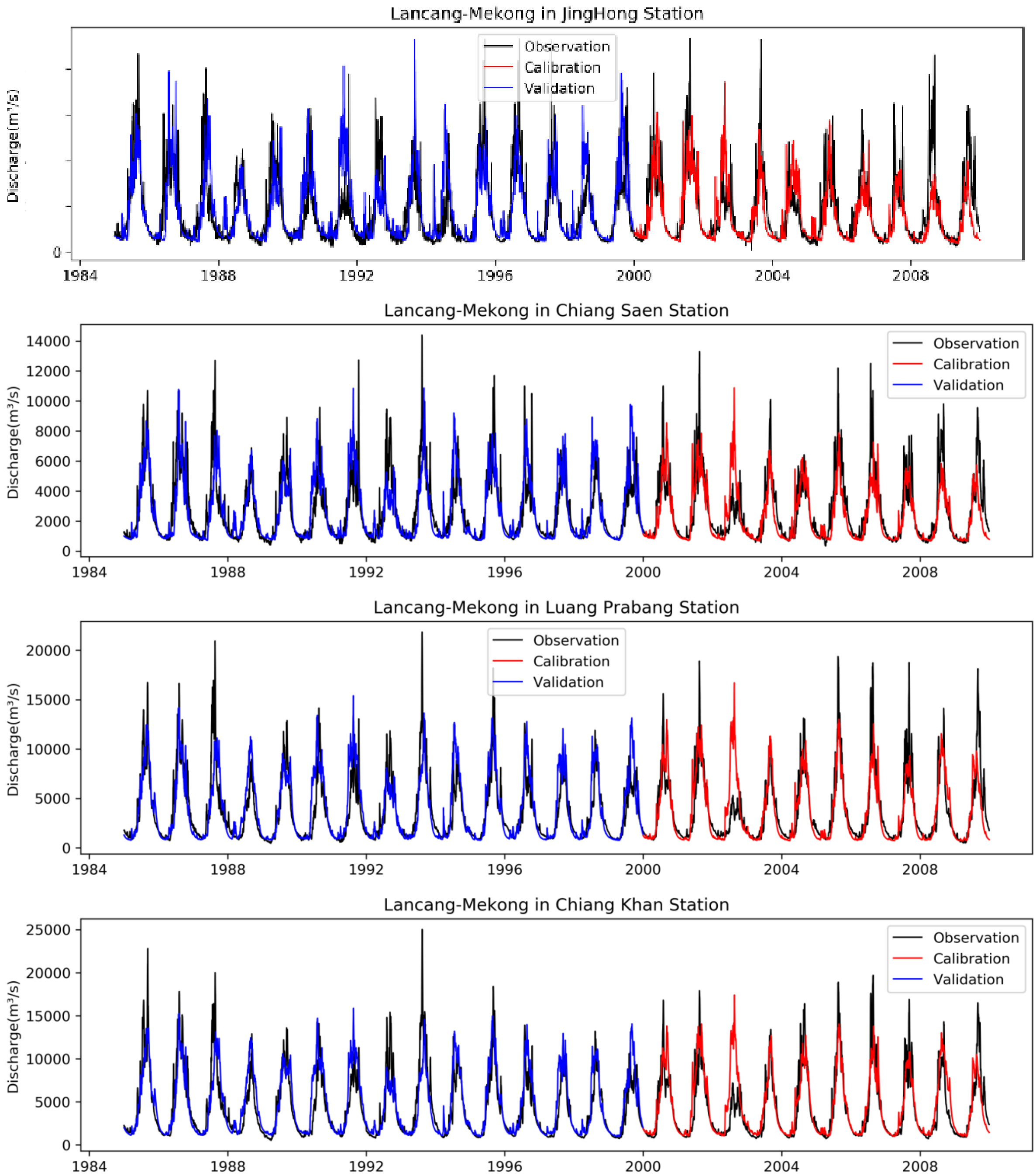
The THREW model is used to simulate the rainfall-runoff in the Lancang-Mekong River Basin. The LMRB was divided into 595 sub-basins based on the 1 km^2 × 1 km^2 resolution of Digital Elevation Model (DEM) using the Pfafstetter method. The 33 sub-basins, whose area is larger than 5000 km^2, were divided into smaller ones. Thus, the study area was finally divided into 651 REWs.

Figure D-3 shows the simulated and observed daily streamflow at 9 stations. The NSE at Jinghong during the validation period is around 0.85, and those of the other stations are around or larger than 0.9. In general, the THREW model performs exceptionally well in simulating the runoff in the LMRB.

D.2 Reference of Annex D

Tian, F., Hu, H., Lei, Z., and Sivapalan, M. (2006). Extension of the Representative Elementary Watershed approach for cold regions via explicit treatment of energy related processes, Hydrol. Earth Syst. Sci., 10, 619–644, https://doi.org/10.5194/hess-10-619-2006 .

D.3 Calibration (2000–2009) and validation (1985–1999) of the THREW model



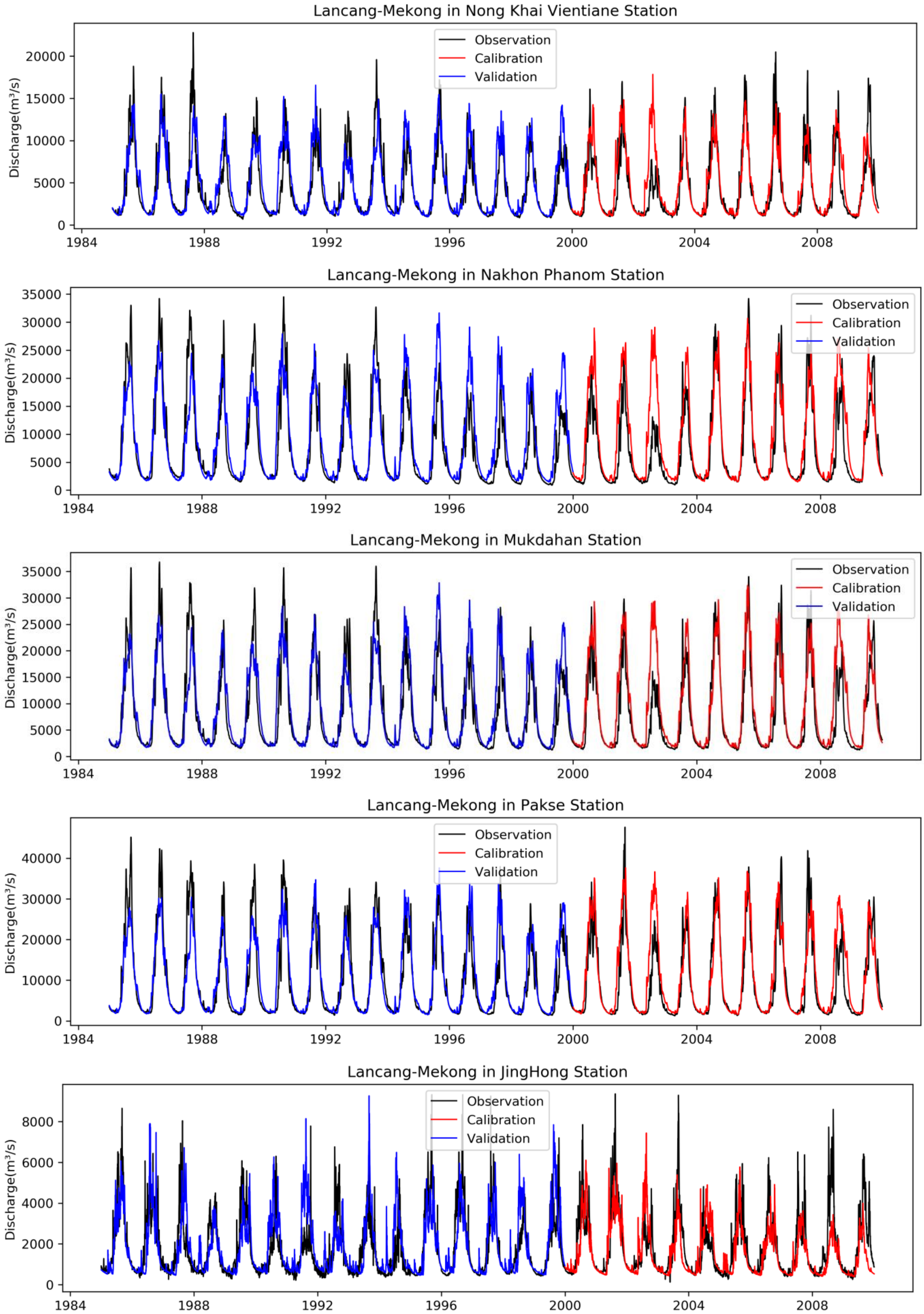


Figure D-3. Results of THREW Calibration for 2000–2009 and validation for 1985–1999 at key stations on the Lancang-Mekong mainstream

ANNEX E – SOIL AND WATER ASSESSMENT TOOL (SWAT)

E.1 Description of the SWAT Model

SWAT is the acronym for Soil and Water Assessment Tool, a river basin scale, continuous time and spatially distributed model developed for the USDA Agricultural Research Service in the early 1990s (Neitsch et al., 2011). It plays an important role in the hydrological model and is widely applied around the world for its powerful function, advanced model structure, and high-efficient calculation. The model is one of the distributed hydrological models based on spatial data offered by GIS and Remote Sensing (Zhao et al., 2013). It is a process-based, continuous physically based distributed parameter river basin model that simulates water, sediment and pollutant yields to assist water resources manager assess the impact of land use management on water, and diffuse pollution for large ungauged catchments with different soil types, land use and management practices (Zhang et al., 2019).

The major model includes 8 components such as hydrology, meteorology, sediment, soil temperature, crop growth, nutrients, pesticides/insecticides, and agricultural management, 701 equations and 1.013 intermediate variables (Zhang et al., 2013). It could simulate the processes of surface runoff, infiltration, side-stream, groundwater flow, reflux, snowmelt runoff, soil temperature, soil moisture, evapotranspiration, sediment yield, sediment transport, crop growth, basin water quality, pesticides/insecticides and nutrient movement through the hydrologic cycle of the watershed system (Abbasi et al., 2019). The hydrologic processes within the model comprise infiltration, percolation, evaporation, plant uptake, lateral flows and groundwater flows including snowfall and snowmelt (Neitsch, 2005). The Modified Soil Conservation Service (SCS), curve number (CN) method is used for the estimation of surface runoff volume. Lateral flow is simulated by kinematic storage model and return flow is estimated by creating a shallow aquifer. The water balance equation (1), which governs the hydrological components of SWAT model (Ruan et al., 2017), is as follows:

$$\boldsymbol{SW_t = SW_o + \sum_{i=0}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right)}$$

Where:

SW_t : The final soil water content (mm H_2O)

SW_0: The initial soil water content on day i (mm H_2O)

t: The time (days)

R_{day}: The amount of precipitation on day i (mm H_2O)

Q_{surf}: The amount of surface runoff on day i (mm H_2O)

E_a: The amount of evapotranspiration on day i (mm H_2O)

W_{seep}: The amount of water entering the vadose zone from the soil profile on day i (mm H_2O)

Q_{gw}: The amount of return flow on day i (mm H_2O)

To calculate the water movement in an HRU, SWAT includes several hydrological processes in the land component such as infiltration, surface runoff, baseflow, lateral flow, evapotranspiration, and canopy storage (Figure E-1).

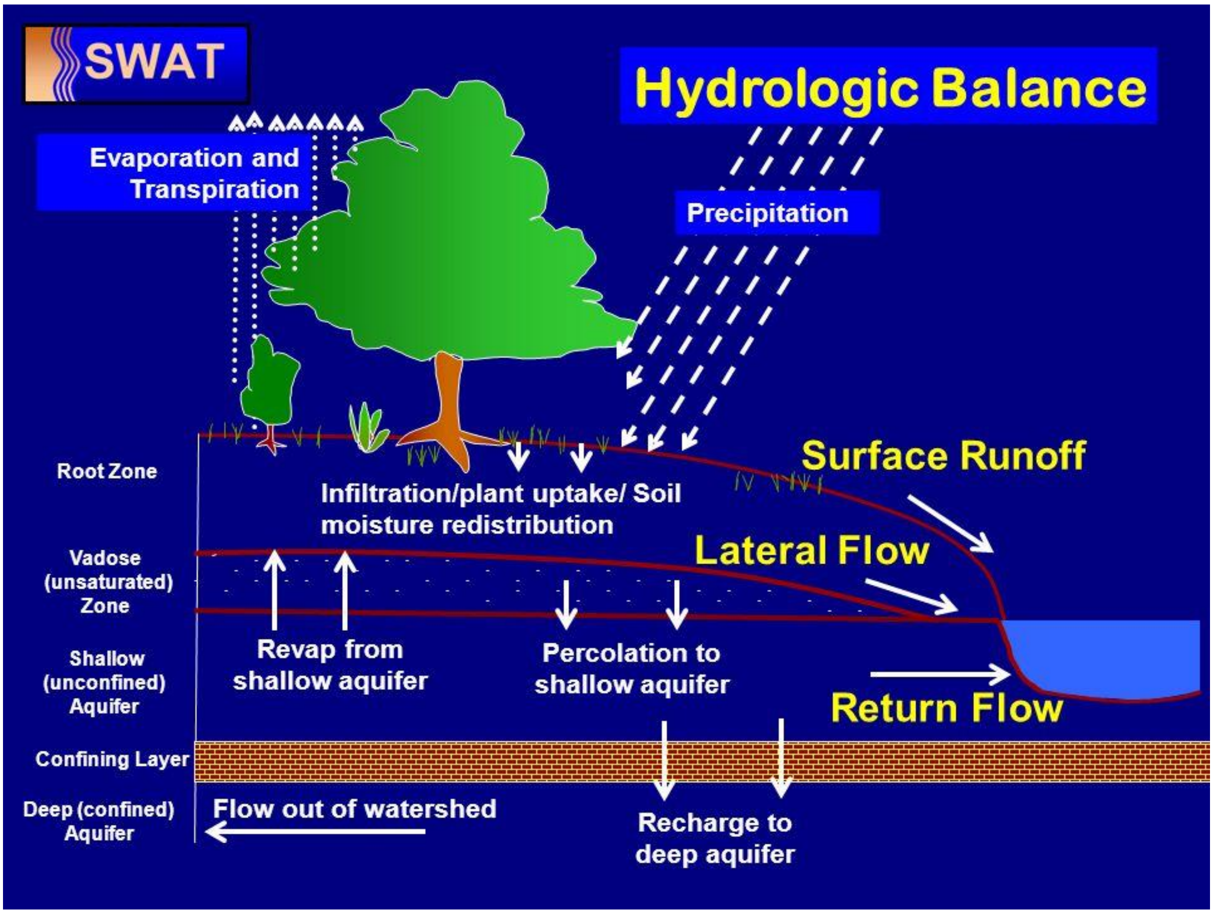


Figure E-1. Schematic representation of water cycle in SWAT.

Infiltration: defines the process by which water from the soil surface enters the soil profile. The rate of infiltration decreases with time until the soil becomes saturated. The "Green-Ampt Mein-Larson" infiltration method calculates the infiltration based on sub-daily precipitation data.

Surface runoff: is an overland flow that occurs along a sloping surface. SWAT models surface runoff volumes and peak runoff rates for each HRU. The surface runoff volume is calculated by using a modification of the SCS curve number method or the "Green-Ampt Mein-Larson" infiltration method.

Return flow: also, baseflow, describes the volume of streamflow contributing from groundwater. The baseflow describes the percolation between shallow and deep aquifers in the SWAT model.

Lateral flow: describes the lateral movement of water in the unsaturated zone of the soil profile (0-2 m).

Evapotranspiration: includes all processes at or near the earth's surface which turn water in the liquid or solid phase into atmospheric water vapor. The evapotranspiration processes comprise evaporation, transpiration (differentiation between potential and actual evapotranspiration) and the sublimation from ice and snow surfaces. SWAT provides three options for calculating potential evapotranspiration: Hargreaves, Priestley-Taylor and Penman-Monteith.

Canopy storage: Canopy storage is the water intercepted by vegetative surfaces where it is available for evapotranspiration.

E.2 Reference of Annex E

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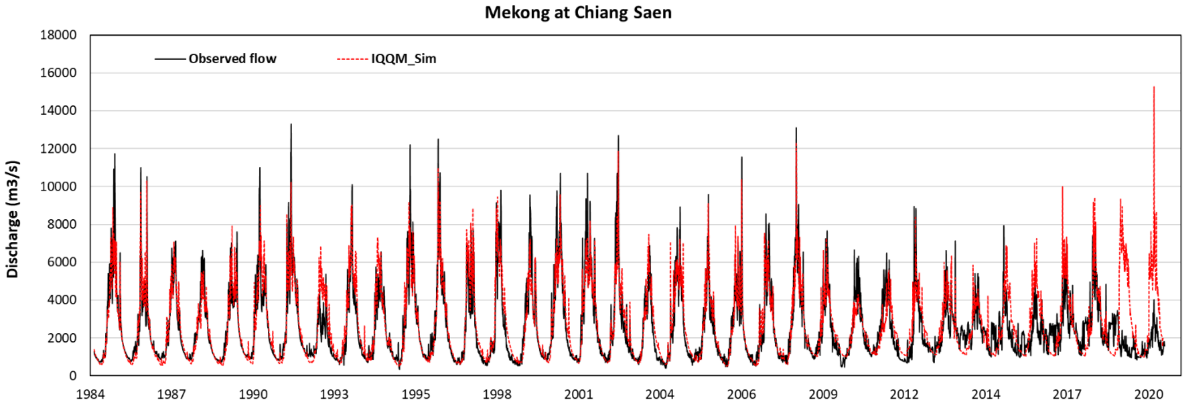
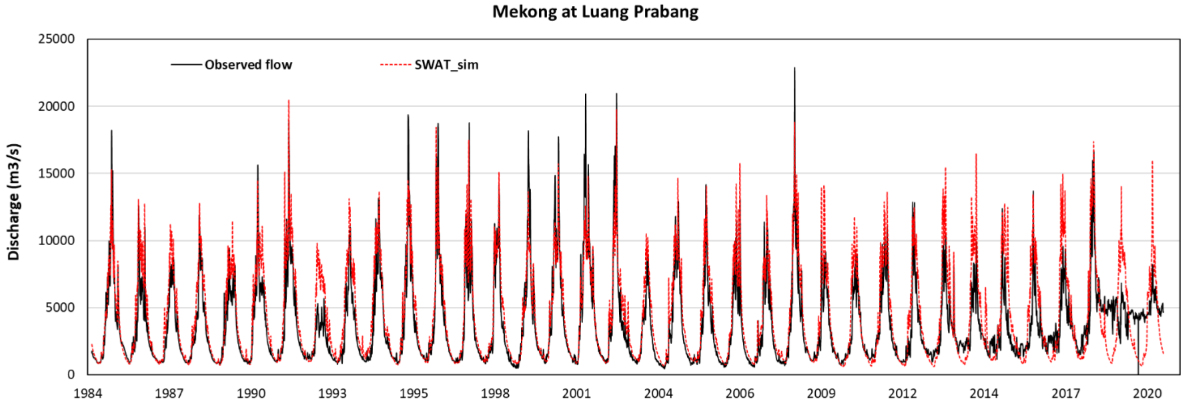
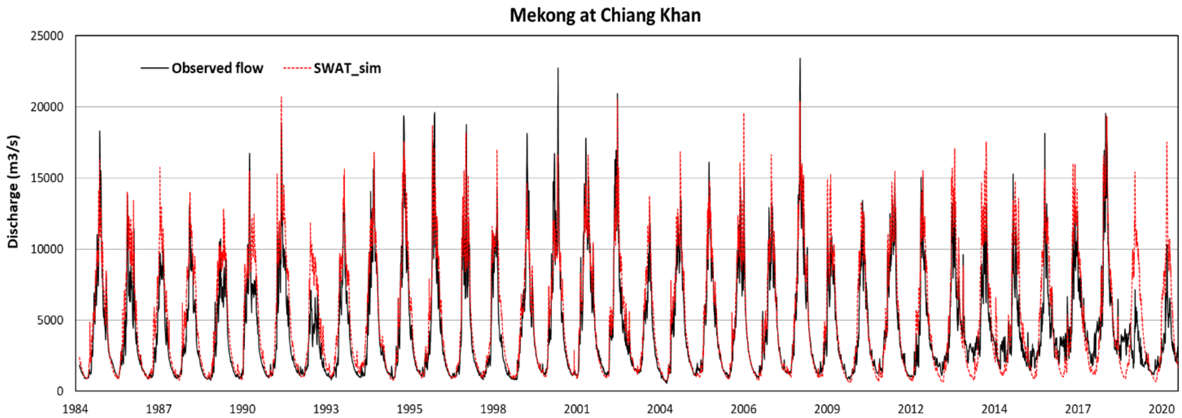
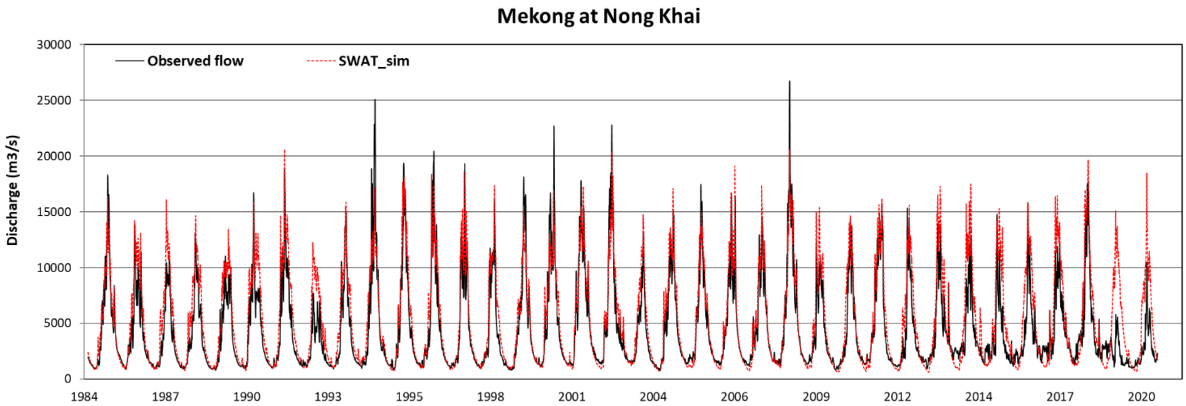
E.3 Calibration (1985–2008) and validation (2009–2020) of SWAT









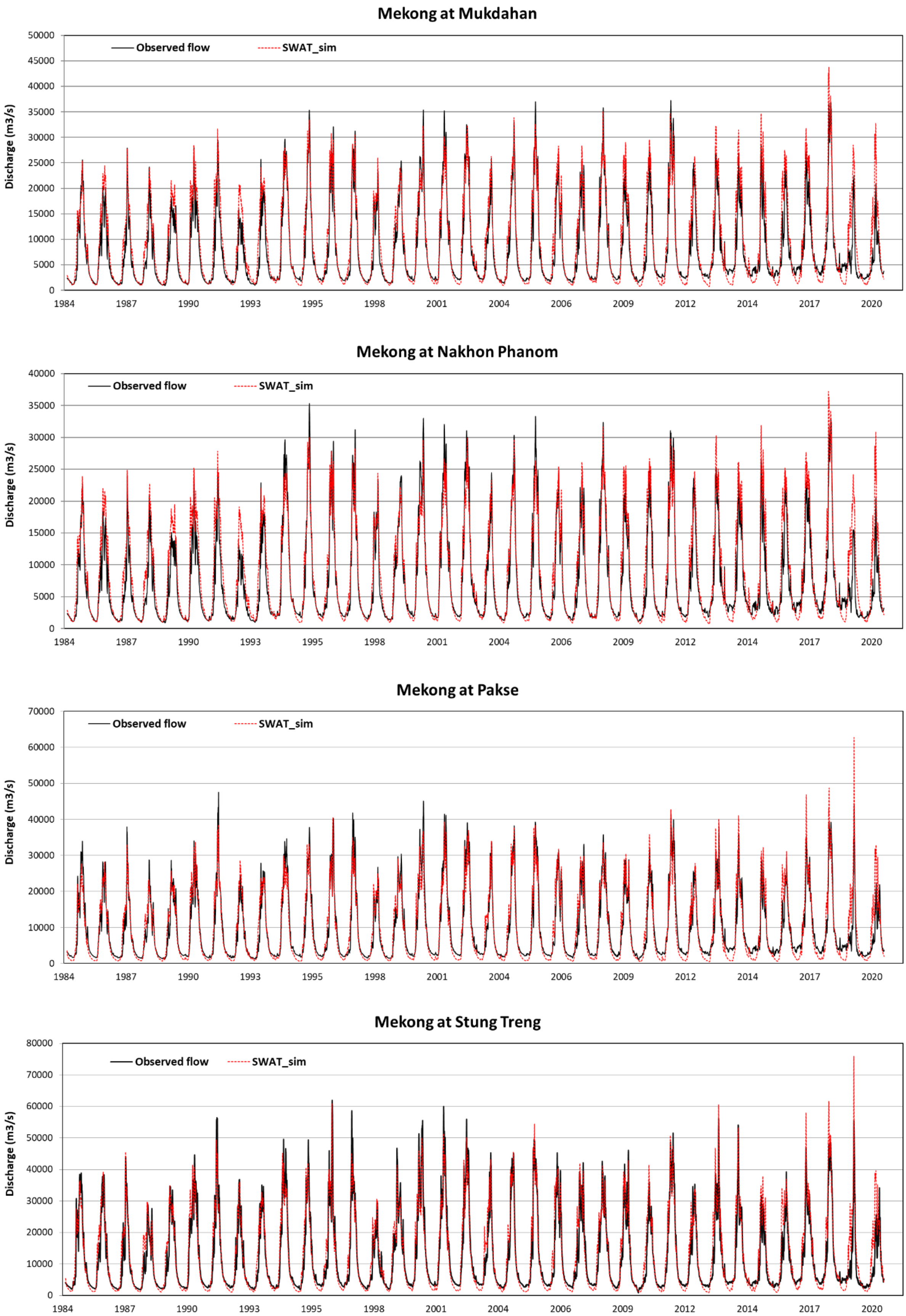


Figure E-2. Results of SWAT Calibration for 1985–2008 and validation for 2009–2020 at key stations on the Mekong mainstream

ANNEX F – SOURCE, HYDROLOGICAL MODELLING PLATFORM

F.1 Overview

Source is an adaptive, customisable hydrological modelling platform that combines water resource assessment with a unique governance modelling capability to produce water accounts and operate rivers according to agreements and treaties.

A new generation tool created to support the transformation of water modelling capability, Source is the outcome of two decades of collaboration between State and Federal Government water organisations, leading universities, water utilities and regional rural water authorities through the eWater Cooperative Research Centre (CRC) and its predecessors the CRC for Catchment Hydrology and the CRC for Freshwater Ecology.

Source can be used for all aspects of Integrated Water Resources Management (IWRM), including hydropower, irrigation, domestic/industrial water demands and ecological management, as illustrated in **Figure F-1**.

Figure F-1. The Source Modelling Platform supporting all aspects of water resource modelling, including supply, demand, land use and climate, from the catchment to the user scale

F.2 Target user group

Source is designed for managers, researchers, modellers to develop computer simulation models of rivers and catchments to understand and explore important aspects of their behaviour and guide decision making.

Information produced by Source is useful for a broader audience of people, including:

- Resource managers, water planners and operators who rely on a model's results and need to understand the general configuration and application of a model but are not necessarily interested in the detail of the model development process.
- Management and government representatives who want to understand how and where model results were obtained.
- Researchers and non-government organisations with an interest in water science use model results and want to understand the model's behaviour.
- People affected by decisions supported by model results or who have a general interest in water use in a river system (e.g. irrigators or environmental groups).

F.3 Flexibility and complexity

Source provides a flexible structure that allows you to select a level of model complexity appropriate to the problem at hand and within any constraints imposed by your available data and knowledge.

F.4 Applications

Source Modelling Platform is the definitive integrated water resource management (IWRM) modelling software for:

- integrated water resource assessments, including agricultural, hydropower, urban, industrial and environmental requirements
- water balance studies from catchment to river basin scale
- water accounting and analysis of supply/demand balances
- inflow forecasting and multi-objective reservoir operations
- resource assessment and allocation policy development and planning
- trade-off analysis to balance sharing and equitable use of scarce water resources
- low flow and drought management
- water quality analysis based on catchment land use scenarios
- impacts of climate change and transboundary transfers
- bulk water systems optimisation, planning and operations including multiple supply options (reservoir/recycling)
- conjunctive groundwater-surface water use analysis.

ANNEX G – STANDARDISED PRECIPITATION INDEX (SPI) AND STANDARDISED PRECIPITATION EVAPOTRANSPIRATION INDEX (SPEI)

G.1 Standardised Precipitation Index (SPI)

The metrics of drought include duration (D), area (A), intensity (I), and severity (S). The number of consecutive months in which the running mean drought index remained below the drought threshold is referred to as duration, while the number of drought events throughout the time is referred to as frequency.

During a drought, intensity is the difference between the drought threshold and the monthly running mean drought index averaged over all months. The cumulative intensity of drought across an area throughout the drought is referred to as severity (Ukkola et al., 2020).

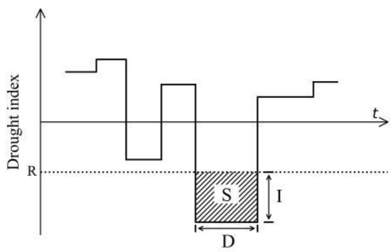


Figure G-1. Variables of drought (S is severity, D is duration, I is intensity, R is the threshold)

The SPI is a meteorological drought monitoring and evaluation indicator that applies on or above the monthly scale and expresses the probability of precipitation occurring in a given period. SPI has been widely used to illustrate meteorological drought in recent years due to its easy access to data, simple calculation, adjustable temporal scale, and regional comparability.

The following is a typical SPI calculation procedure: (1) precipitation series is fitted to a gamma (*Γ)* distribution; (2) a normal standardisation of a skewed probability distribution is performed, and (3) drought is graded using the cumulative frequency of standardised precipitation distribution.

The formula to calculate SPI are as follows (McKee et al., 1993):

$$\mathrm{SPI} = \mathrm{S}\left\{t - \frac{(c_2 t + c_1)t + c_0}{[(d_3 t + d_2)t + d_1]t + 1.0}\right\}, \quad (1)$$

$$\mathrm{t} = \sqrt{ln\frac{1}{G(x)^2}}, \quad (2)$$

where *x* is precipitation sample value; *S* is the positive and negative coefficients of probability density; c_0, c_1, c_2 and d_1, d_2, d_3 are calculation parameters of the simplified approximation analysis formula for converting *Γ* distribution probability into cumulative frequency, and c_0=2.515517, c_1=0.802853,

c_2=0.010328, d_1=1.432788, d_2=0.189269 and d_3=0.001308. *G(x)* is the rainfall distribution probability related to the *Γ* function. According to the probability density integral formula of *Γ* function is:

$$\mathrm{G}(x) = \frac{2}{\beta^{\gamma}\tau(\gamma_0)}\int_0^x x^{\gamma-1}e^{-x/\beta}dx, \qquad x > 0\,, \tag{3}$$

where, *S* = 1 when *G(x)* > 0.5, *S* = -1 when *G(x)* ≤ 0.5.

G.2 Standardised Precipitation Evapotranspiration Index (SPEI)

The method for calculating SPEI is identical to that for the SPI. Rather than using precipitation, SPEI is based on the concept of 'climatic water balance', i.e., the difference between precipitation and potential evapotranspiration (PET), as the input (Beguería et al., 2014).

The Hargreaves method is used to calculate PET (Hargreaves and Samani, 1985). It is a straightforward method that can be used instead of the Penman-Monteith method, which relies solely on temperature observations to calculate reference evapotranspiration (Althoff et al., 2019). The Penman-Monteith and Hargreaves methods show reasonable agreement with reference datasets in previous studies (Droogers and Allen, 2002).

The SPI/SPEI calculation time scale range from 1 to 48 months or longer, and are expressed as SPI1 (SPEI1), SPI2 (SPEI2), and SPI48 (SPEI48) (WMO, 2012). In this study, SPI12/SPEI12 in December was used to investigate the trend and intensity of drought at the annual scale. SPI6/SPEI6 in May and November, calculated based on the data of the past six months, were used to represent the dry season and the wet season, respectively. SPI3/SPEI3 were used for drought duration and frequency analysis, this is because the 3-month scale index could reflect drought characteristics and the widespread impact of seasonal drought in tropical and temperate regions. They can be more effective in highlighting available moisture conditions in primary agricultural regions (Guo, et al., 2017; WMO, 2012; Ukkola et al., 2020).

The drought grades of SPEI/SPI are evaluated according to the Chinese National Standard <Grades of Meteorological Drought> (GB / T 20481-2017) and the WMO User Guide. The detail is shown in **Table G-1**. It indicates that the two grading systems have the same thresholds for moderate, severe, and exceptional droughts.

Table G-1. Grades of SPEI/SPI

Grade	Type	SPEI/SPI	
China	China / WMO	WMO	China
I	No drought	>0.0	>-0.5
II	Mild drought	-1.0 to 0.0	-1.0 to -0.5
III	Moderate drought	-1.5 to -1.0	-1.5 to -1.0
IV	Severe drought	-2.0 to -1.5	-2.0 to -1.5
V	Exceptional drought	≤-2.0	≤-2.0

G.3 References of Annex G

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Ukkola, A. M., De Kauwe, M. G., Roderick, M. L., Abramowitz, G., & Pitman, A. J. (2020). Robust Future Changes in Meteorological Drought in CMIP6 Projections Despite Uncertainty in Precipitation. *Geophysical Research Letters, 47*(11), e2020GL087820. https://doi.org/10.1029/2020GL087820

WMO. (2012). Standardized precipitation index: user guide.

ANNEX H – DAILY HYDROGRAPHS 2000-2009 AND 2010-2020

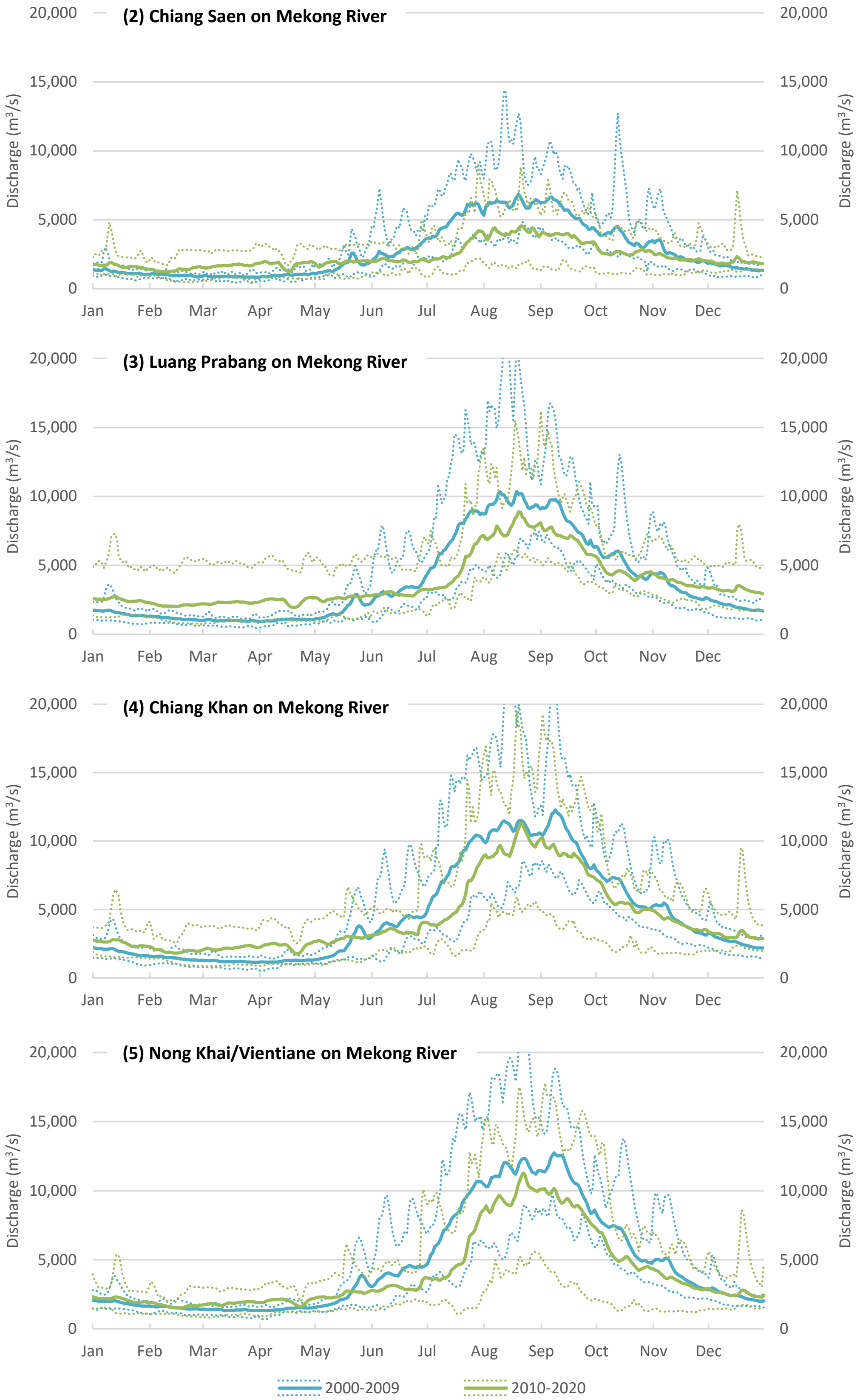


Figure H-1. Daily discharge hydrograph on the mainstream from Chiang Saen to Nong Khai/Vientiane for 2000–2009 (blue) and 2010–2022 (green)

Figure H–2. Daily discharge hydrograph on the mainstream from Nakhon Phanom/Thakhek to Stung Treng for 2000–2009 (blue) and 2010–2022 (green)

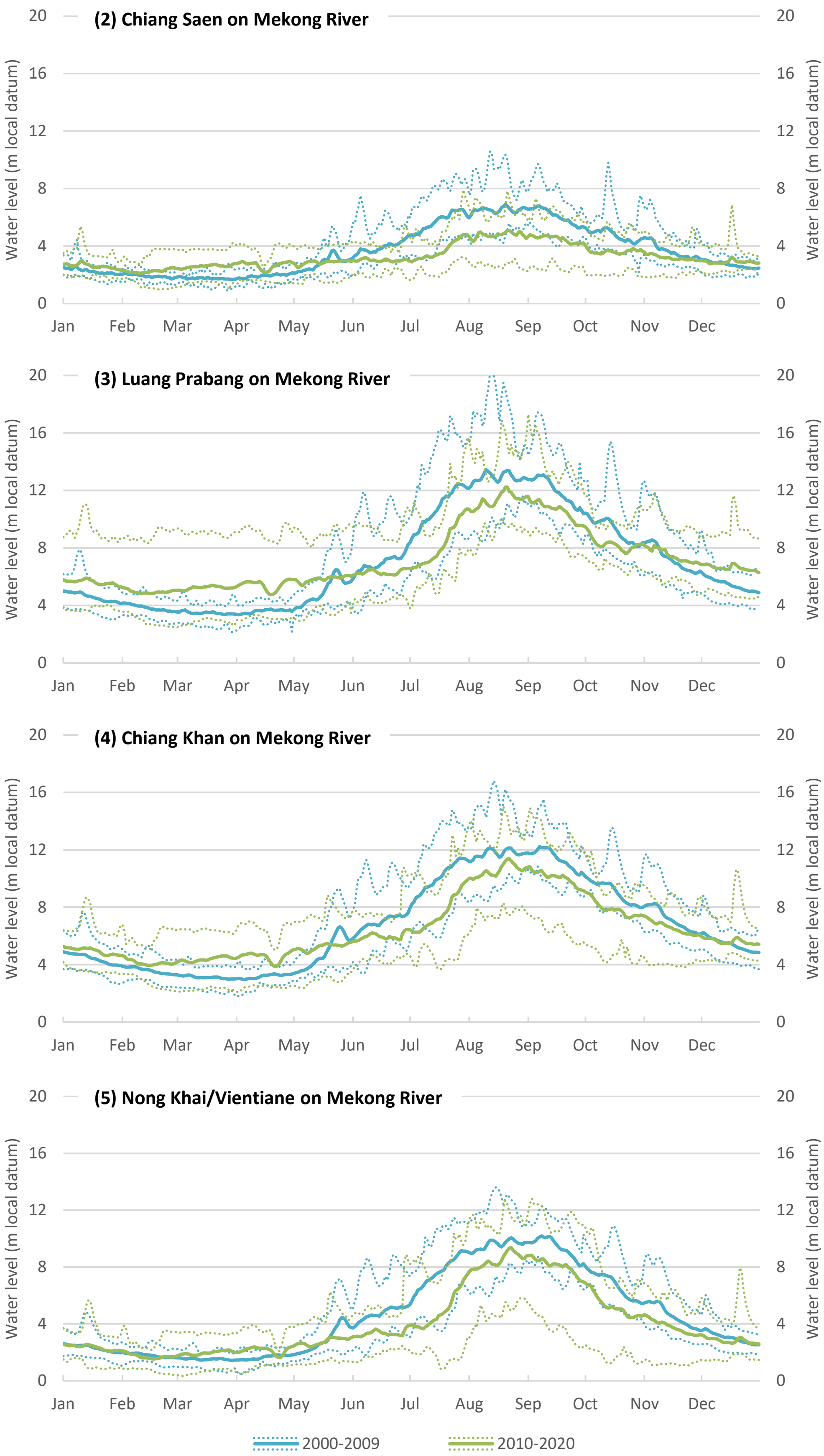


Figure H-3. Daily water level hydrograph on the mainstream from Chiang Saen to Nong Khai/Vientiane for 2000–2009 (blue) and 2010–2022 (green)

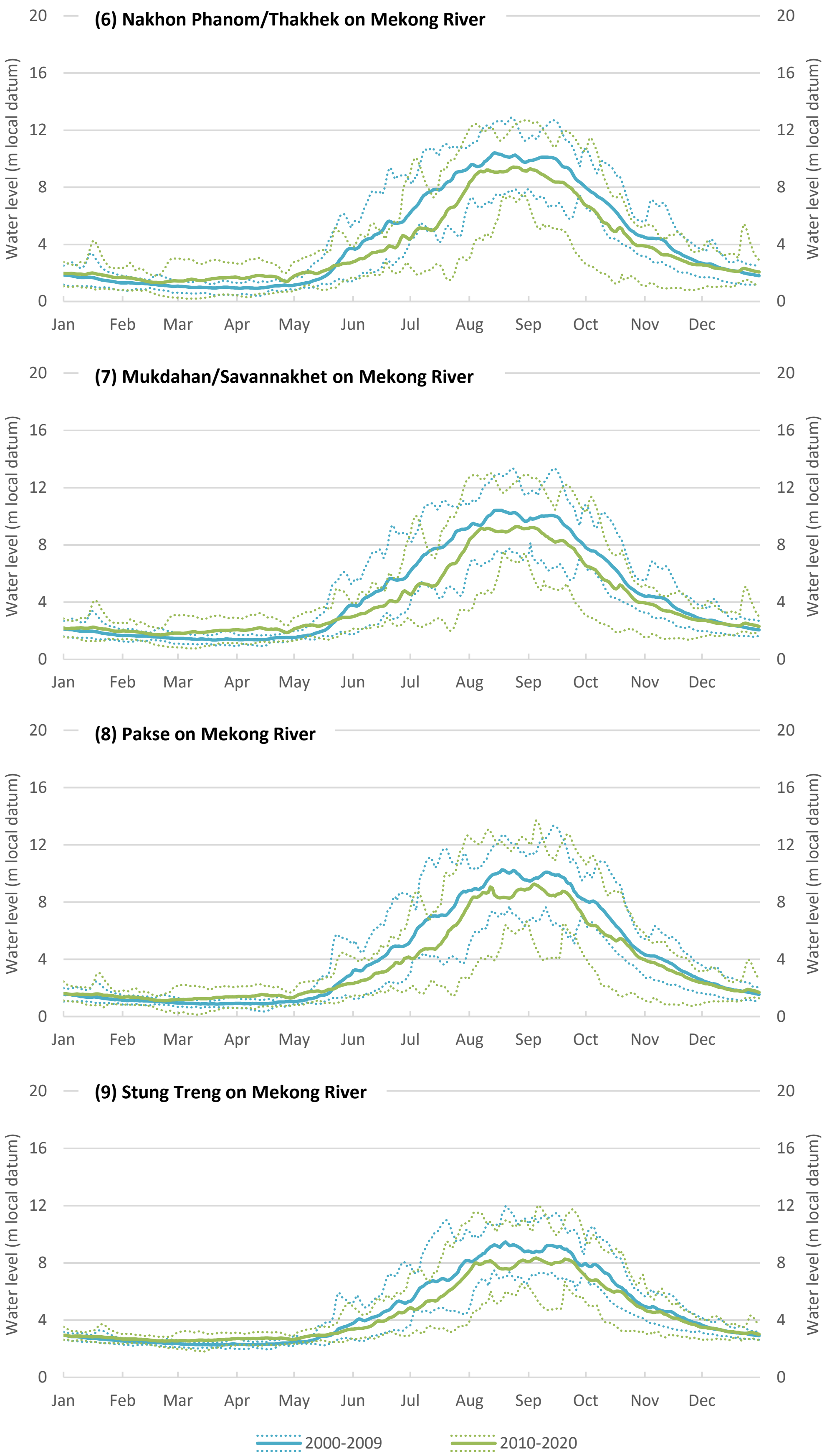


Figure H-4. Daily water level hydrograph on the mainstream from Nakhon Phanom/Thakhek to Stung Treng for 2000–2009 (blue) and 2010–2022 (green)

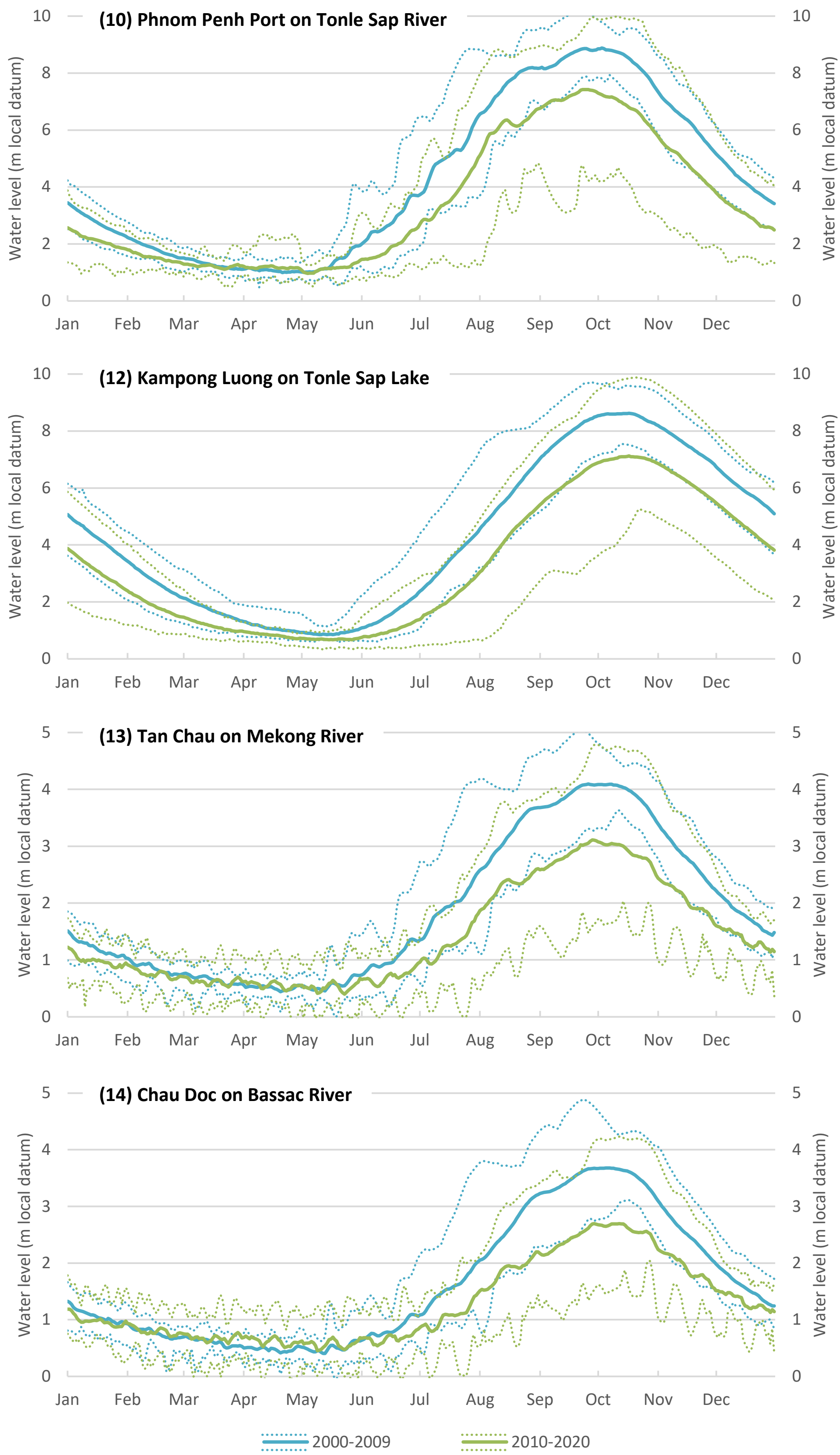


Figure H-5. Daily water level hydrograph at Phnom Penh Port, Kampong Luong, Tan Chau and Chau Doc for 2000–2009 (blue) and 2010–2022 (green)

ANNEX I – DAILY ACCUMULATED VOLUME FOR 2000–2009 AND 2010–2020

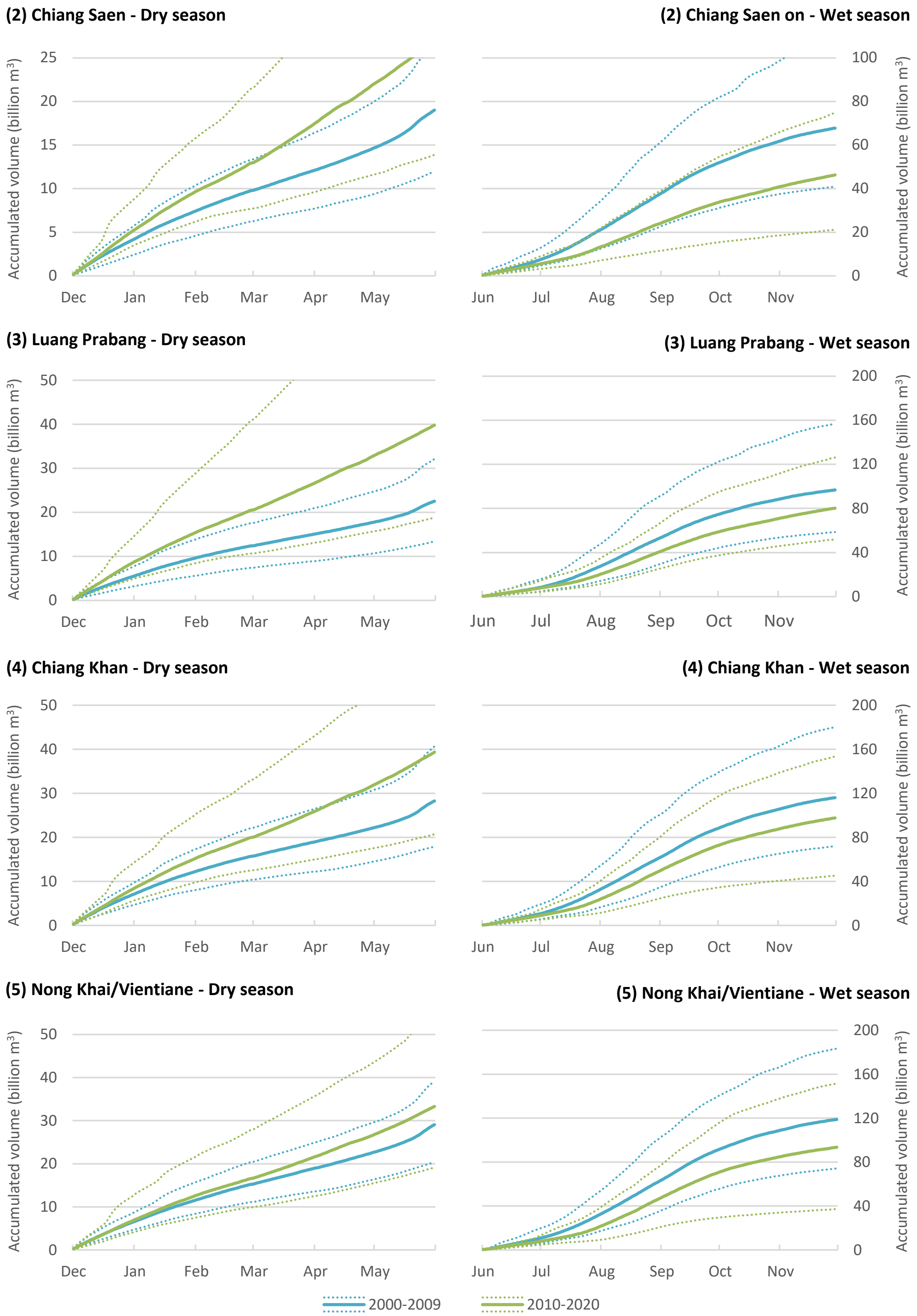


Figure I-1. Daily accumulated volume from Chiang Saen to Nong Khai/Vientiane for dry and wet seasons for 2000–2009 (blue) and 2010–2020 (green)

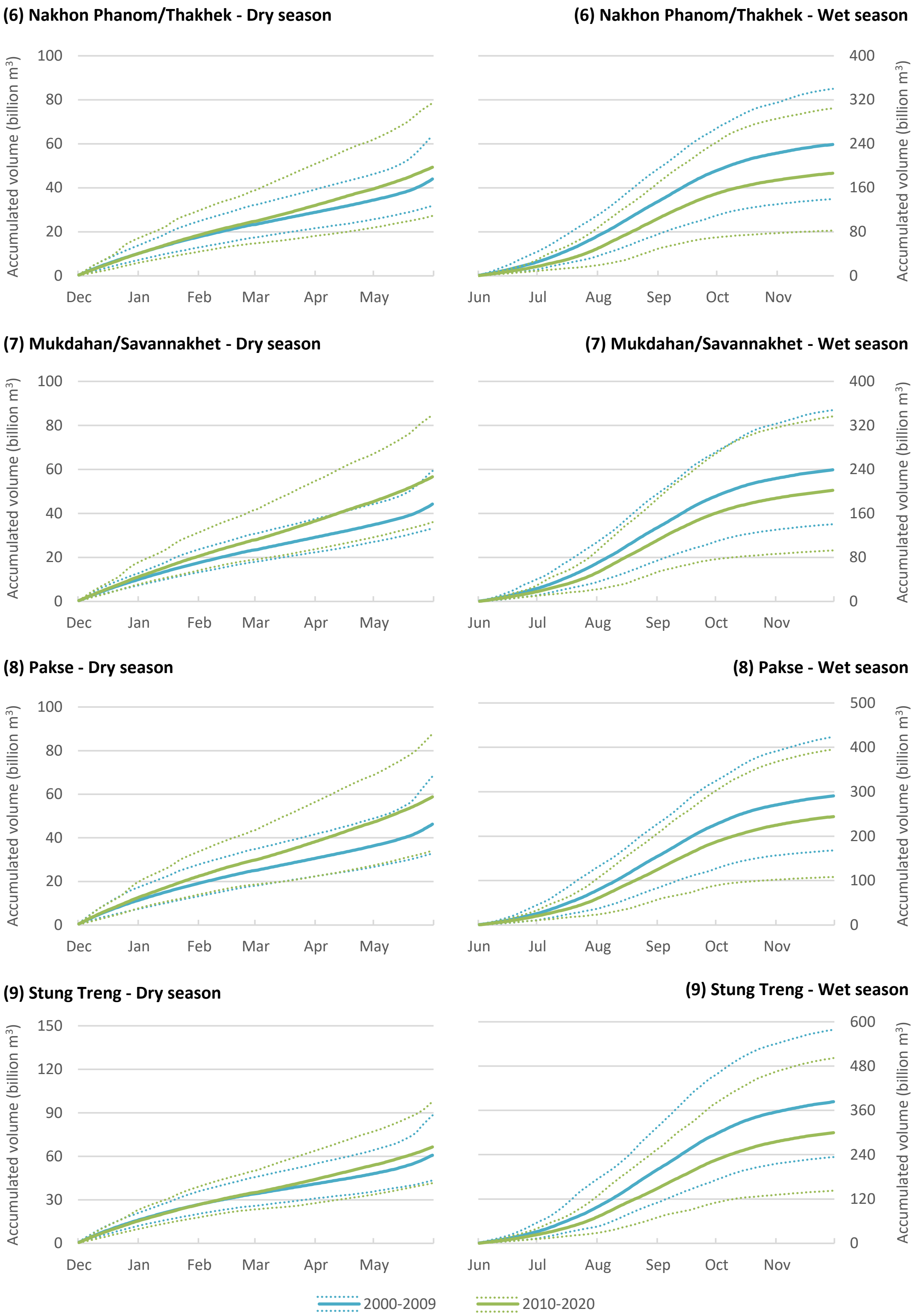


Figure I-2. Daily accumulated volume from Chiang Saen to Nong Khai/Vientiane for dry and wet seasons for 2000–2009 (blue) and 2010–2020 (green)

ANNEX J – DAILY OBSERVED REVERSE FLOW TO THE TONLE SAP LAKE FOR 2000–2009 AND 2010–2020

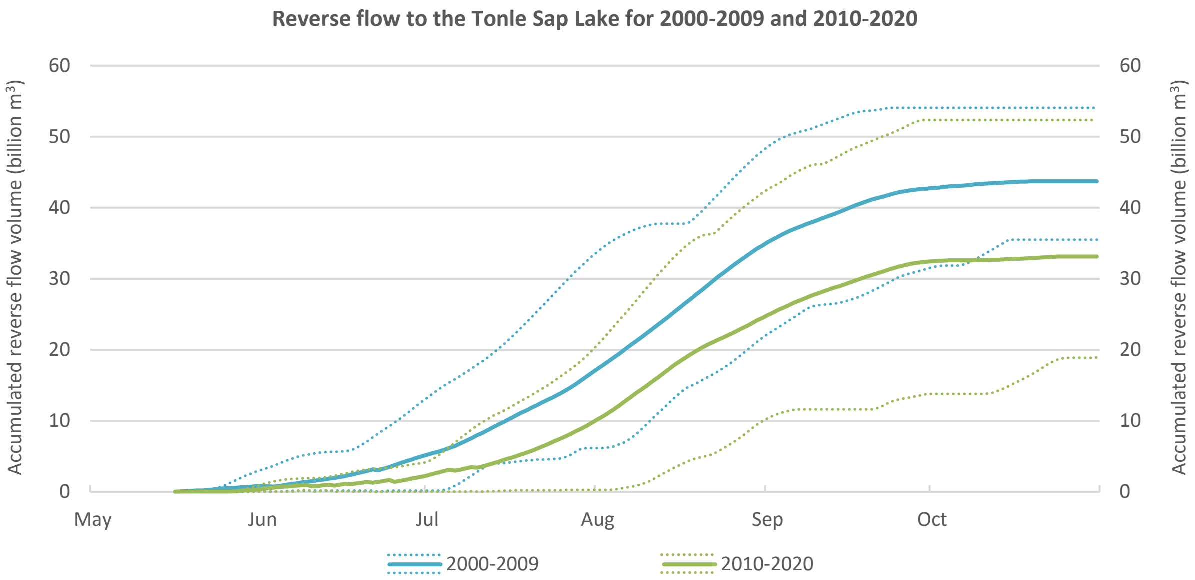


Figure J-1. Daily observed (min–max–average lines) reverse flow to the Tonle Sap Lake for 2000–2009 (blue) and 2010–2020 (green)

ANNEX K – CONTRIBUTION RATIO OF THE SIMULATED SEASONAL VOLUME OF THE MAJOR TRIBUTARIES TO MAINSTREAM STATIONS ALONG THE MEKONG RIVER FOR 2000–2009 AND 2010–2020

Table K-1. Contribution ratio of the simulated wet season volume of the major tributaries to mainstream stations along the Mekong River for 2000–2009 and 2010–2020

Contributing tributaries to mainstream stations (%)	Lancang	Nam Barrier	Nam Ou	Nam Ngum	Nam Theun	Nam Songkhram	Se Bang Hieng	Nam Mun	Se Done	Sekong	Sesan	Srepok
2000–2009												
Chiang Saen	65.3	13.4	–	–	–	–	–	–	–	–	–	–
Luang Prabang	38.5	7.9	11.6	–	–	–	–	–	–	–	–	–
Chiang Khan	32.4	6.7	9.7	–	–	–	–	–	–	–	–	–
Nong Khai/Vientiane	30.8	6.3	9.3	–	–	–	–	–	–	–	–	–
Nakhon Phanom/Thakhek	15.1	3.1	4.5	14.6	10.1	9.7	–	–	–	–	–	–
Mukdahan/Savannakhet	14.7	3.0	4.4	14.2	9.8	9.5	–	–	–	–	–	–
Pakse	12.5	2.6	3.8	12.1	8.4	8.0	2.4	10.3	1.1	–	–	–
Stung Treng	9.1	1.9	2.7	8.8	6.1	5.8	1.7	7.5	0.8	9.4	6.8	7.8
2010-2020												
Chiang Saen	60.9	12.9	–	–	–	–	–	–	–	–	–	–
Luang Prabang	38.8	8.2	13.0	–	–	–	–	–	–	–	–	–
Chiang Khan	32.6	6.9	11.0	–	–	–	–	–	–	–	–	–
Nong Khai/Vientiane	30.6	6.5	10.3	–	–	–	–	–	–	–	–	–
Nakhon Phanom/Thakhek	13.7	2.9	4.6	12.7	13.2	9.7	–	–	–	–	–	–
Mukdahan/Savannakhet	13.3	2.8	4.5	12.4	12.8	9.4	–	–	–	–	–	–
Pakse	11.5	2.4	3.9	10.7	11.1	8.1	1.7	9.9	1.0	–	–	–
Stung Treng	8.2	1.7	2.8	7.6	7.9	5.8	1.2	7.0	0.7	9.2	7.3	9.1

Table K-2. Contribution ratio of the simulated dry season volume of the major tributaries to mainstream stations along the Mekong River for 2000–2009 and 2010–2020

Contributing tributaries to mainstream stations (%)	Lancang	Nam Barrier	Nam Ou	Nam Ngum	Nam Theun	Nam Songkhram	Se Bang Hieng	Nam Mun	Se Done	Sekong	Sesan	Srepok
2000–2009												
Chiang Saen	70.6	10.4	–	–	–	–	–	–	–	–	–	–
Luang Prabang	60.9	9.0	4.4	–	–	–	–	–	–	–	–	–
Chiang Khan	42.6	6.3	3.1	–	–	–	–	–	–	–	–	–
Nong Khai/Vientiane	41.4	6.1	3.0	–	–	–	–	–	–	–	–	–
Nakhon Phanom/Thakhek	24.8	3.6	1.8	11.7	9.0	6.5	–	–	–	–	–	–
Mukdahan/Savannakhet	24.8	3.7	1.8	11.7	9.0	6.5	–	–	–	–	–	–
Pakse	23.0	3.4	1.7	10.9	8.4	6.0	1.5	5.2	0.6	–	–	–
Stung Treng	15.5	2.3	1.1	7.3	5.6	4.0	1.0	3.5	0.4	12.0	6.7	10.1
2010–2020												
Chiang Saen	66.7	10.8	–	–	–	–	–	–	–	–	–	–
Luang Prabang	57.7	9.4	5.1	–	–	–	–	–	–	–	–	–
Chiang Khan	40.9	6.6	3.6	–	–	–	–	–	–	–	–	–
Nong Khai/Vientiane	39.9	6.5	3.5	–	–	–	–	–	–	–	–	–
Nakhon Phanom/Thakhek	23.4	3.8	2.1	11.3	10.1	6.3	–	–	–	–	–	–
Mukdahan/Savannakhet	23.4	3.8	2.1	11.3	10.1	6.3	–	–	–	–	–	–
Pakse	21.6	3.5	1.9	10.5	9.3	5.8	1.1	5.5	0.5	–	–	–
Stung Treng	14.5	2.3	1.3	7.0	6.2	3.9	0.7	3.6	0.3	12.0	6.8	11.1

Note: Simulated volume at Jinghong is used for a flow contribution from the Lancang River.

ANNEX L – VARIATION OF DROUGHT FREQUENCY BETWEEN 2000–2009 AND 2010–2020

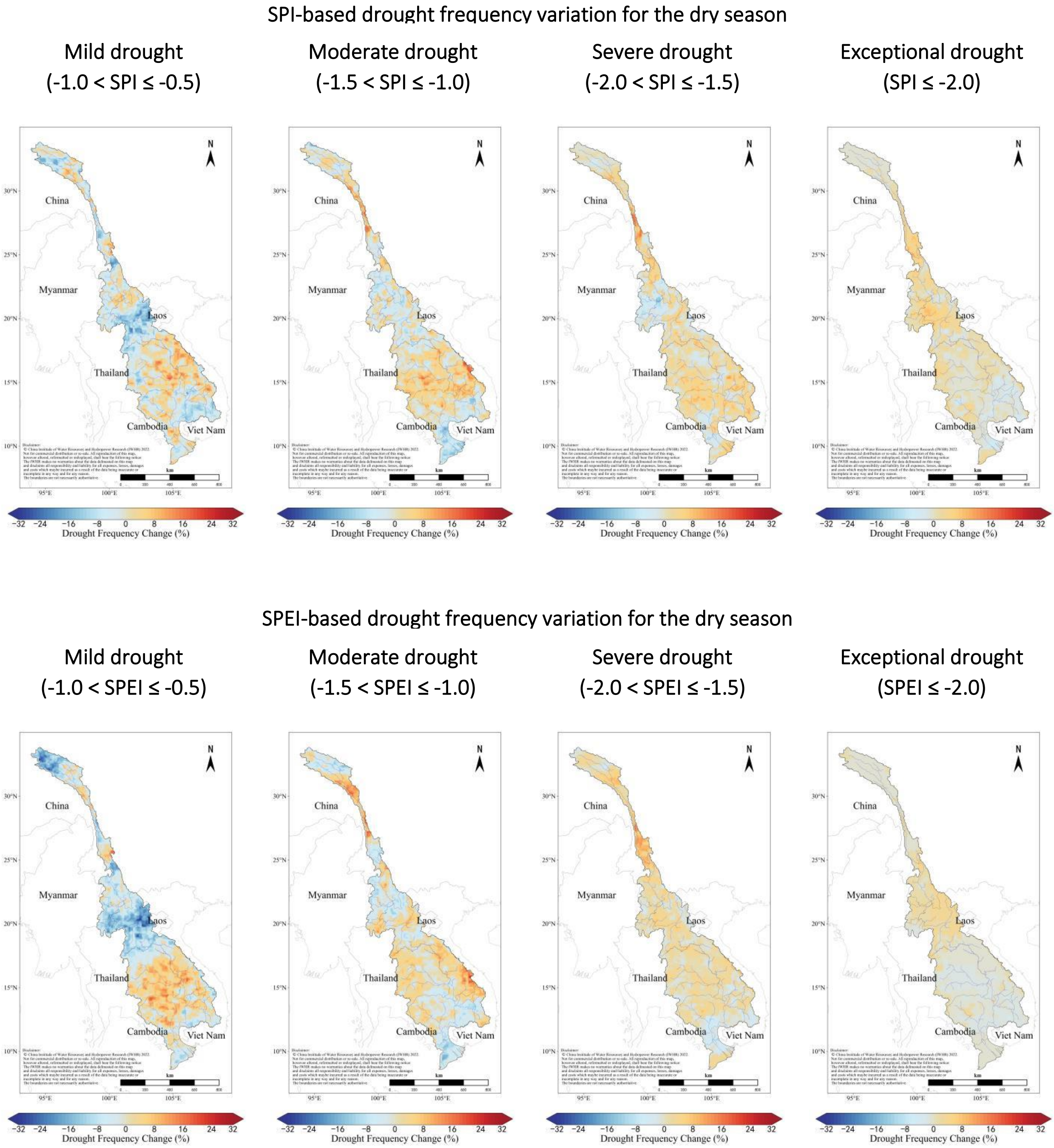
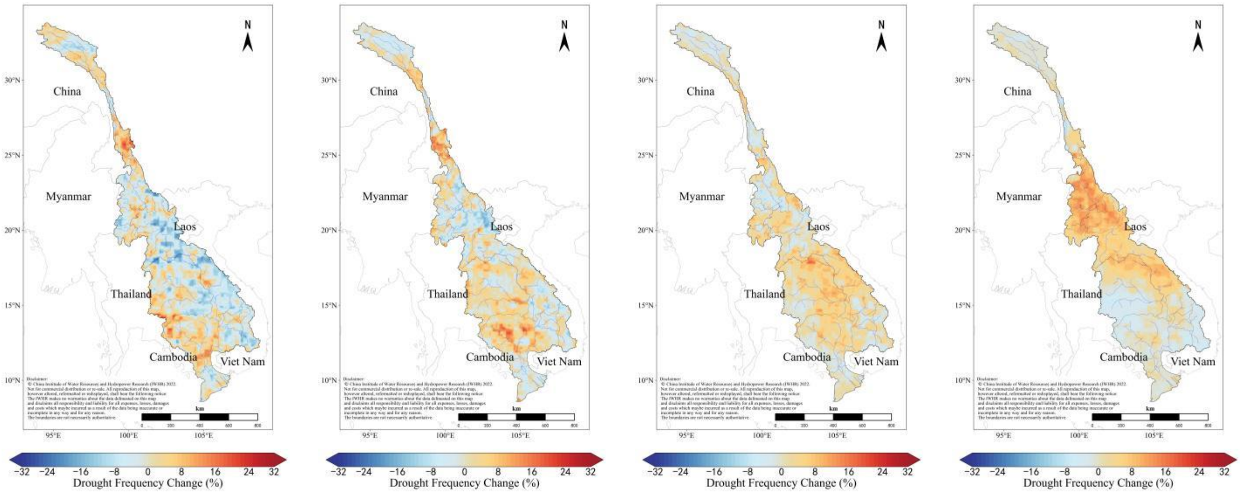


Figure L-1. Variation of dry season drought frequency between 2000–2009 and 2010–2020 based on ERA5-Land dataset

SPI-based drought frequency variation for the wet season

Mild drought (-1.0 < SPI ≤ -0.5)	Moderate drought (-1.5 < SPI ≤ -1.0)	Severe drought (-2.0 < SPI ≤ -1.5)	Exceptional drought (SPI ≤ -2.0)



SPEI-based drought frequency variation for the wet season

Mild drought (-1.0 < SPEI ≤ -0.5)	Moderate drought (-1.5 < SPEI ≤ -1.0)	Severe drought (-2.0 < SPEI ≤ -1.5)	Exceptional drought (SPEI ≤ -2.0)

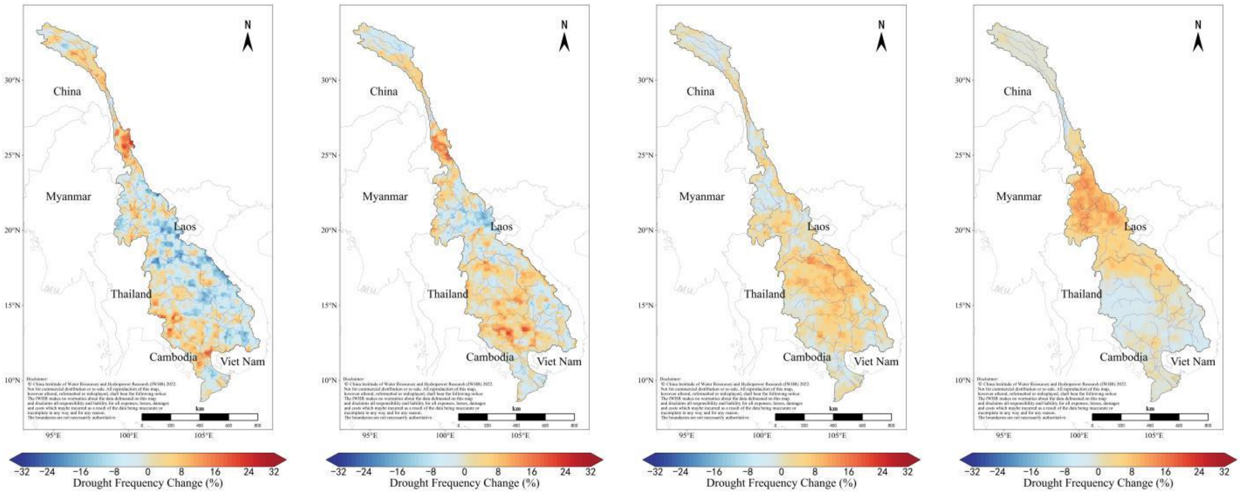


Figure L-2. Variation of wet season drought frequency between 2000–2009 and 2010–2020 based on ERA5-Land dataset

ANNEX M – VARIATION OF DROUGHT DURATION BETWEEN 2000–2009 AND 2010–2020

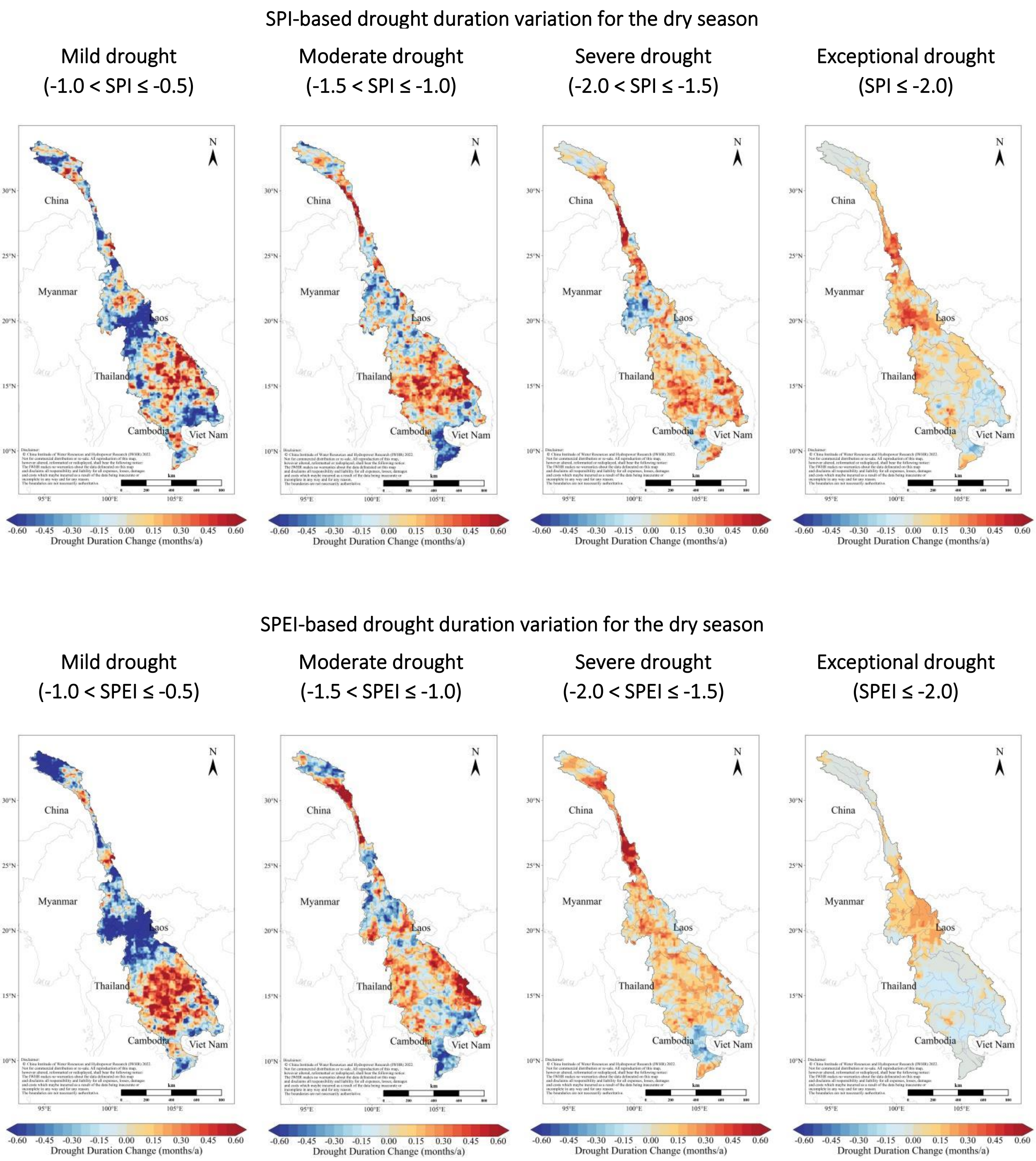
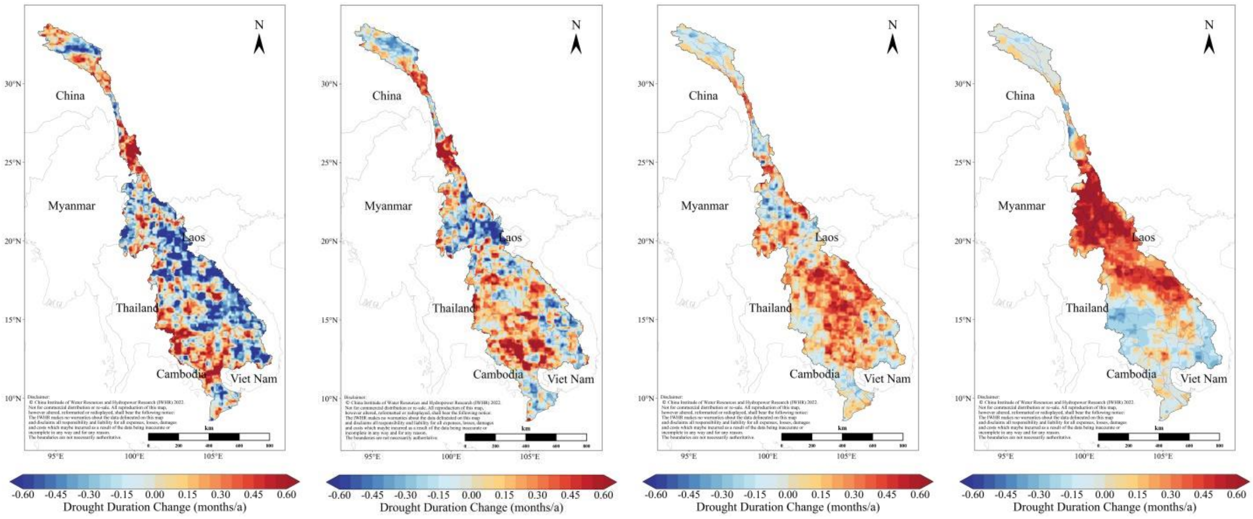


Figure M-1. Variation of dry season drought duration between 2000–2009 and 2010–2020 based on ERA5-Land dataset

SPI-based drought duration variation for the wet season

Mild drought (-1.0 < SPI ≤ -0.5)	Moderate drought (-1.5 < SPI ≤ -1.0)	Severe drought (-2.0 < SPI ≤ -1.5)	Exceptional drought (SPI ≤ -2.0)



SPEI-based drought duration variation for the wet season

Mild drought (-1.0 < SPEI ≤ -0.5)	Moderate drought (-1.5 < SPEI ≤ -1.0)	Severe drought (-2.0 < SPEI ≤ -1.5)	Exceptional drought (SPEI ≤ -2.0)

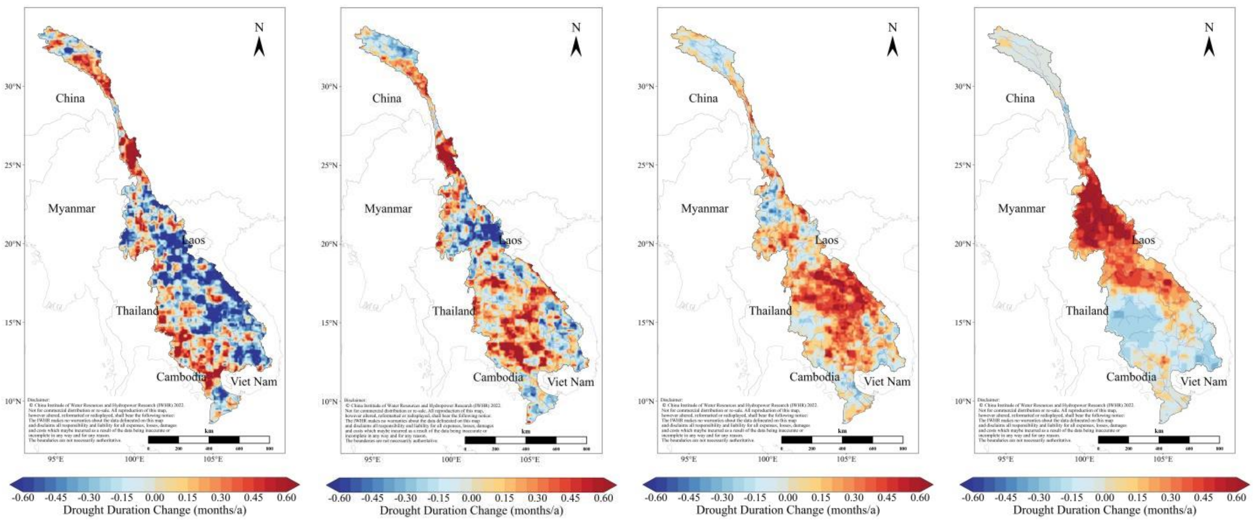


Figure M-2. Variation of wet season drought duration between 2000–2009 and 2010–2020 based on ERA5-Land dataset

ANNEX N – VARIATION OF DROUGHT INTENSITY BETWEEN 2000–2009 AND 2010–2020

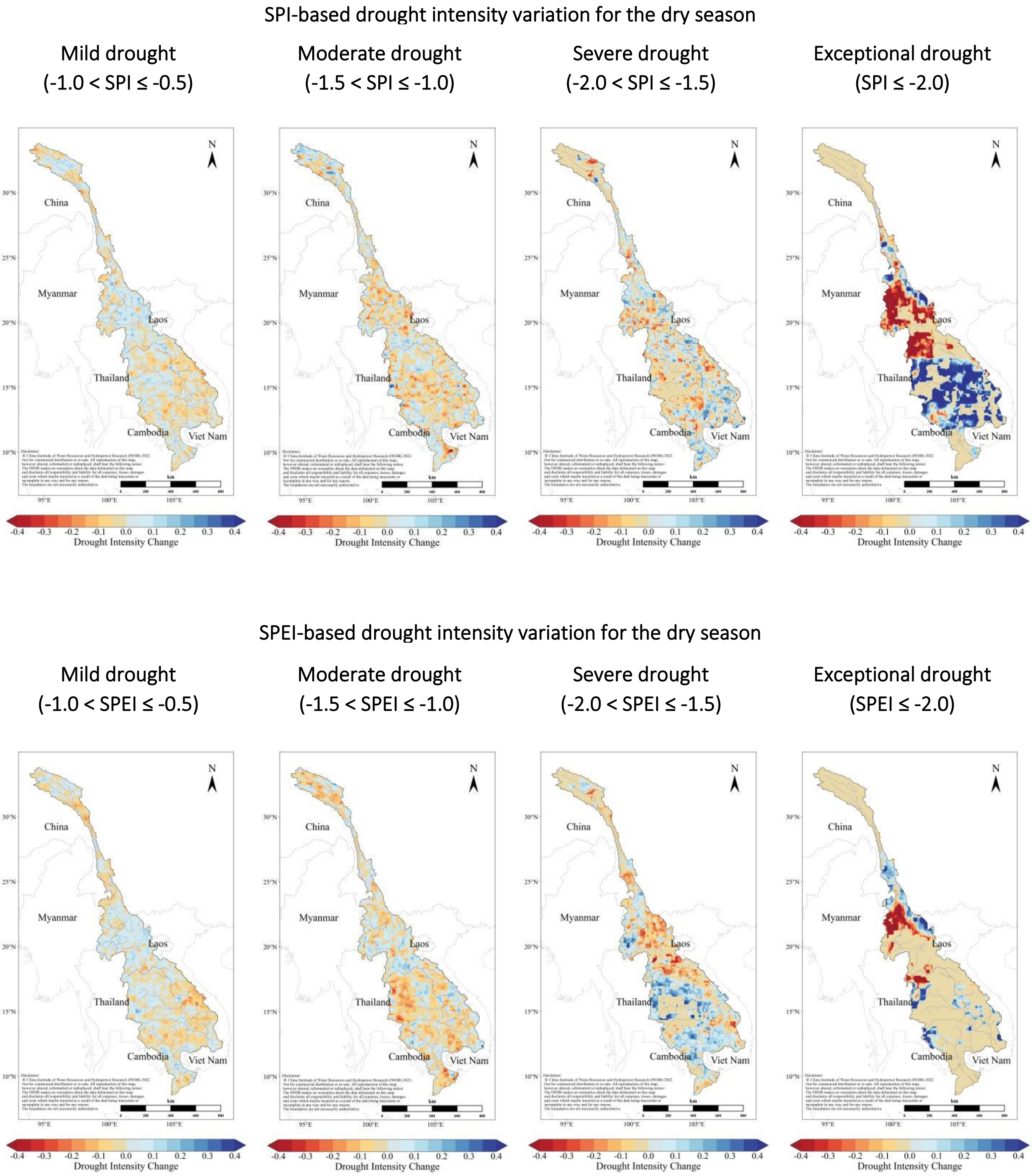
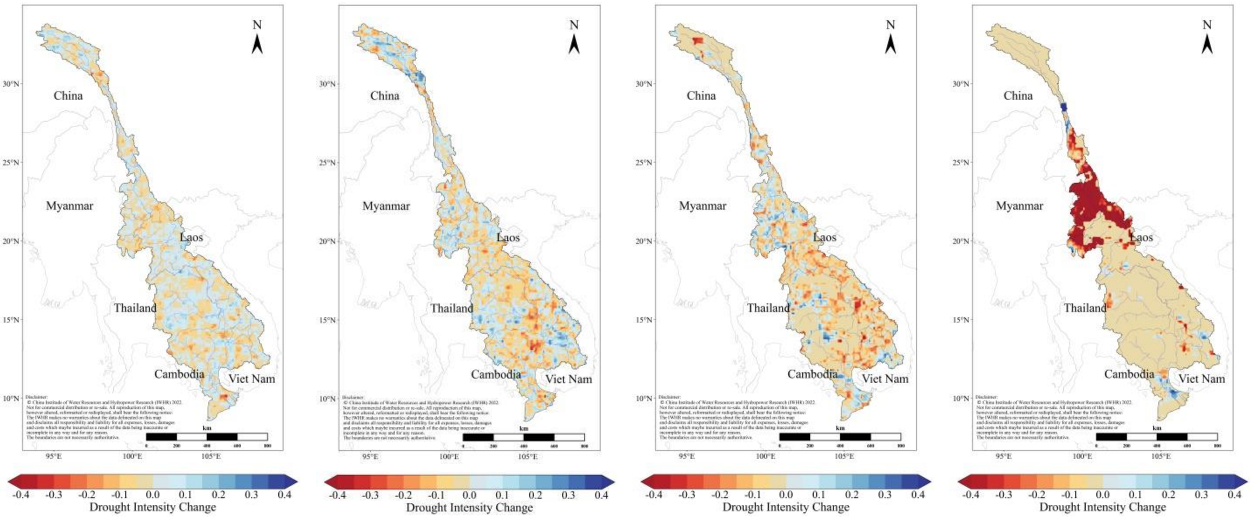


Figure N-1. Variation of dry season drought duration between 2000–2009 and 2010–2020 based on ERA5-Land dataset

SPI-based drought intensity variation for the wet season

Mild drought (-1.0 < SPI ≤ -0.5)	Moderate drought (-1.5 < SPI ≤ -1.0)	Severe drought (-2.0 < SPI ≤ -1.5)	Exceptional drought (SPI ≤ -2.0)



SPEI-based drought intensity variation for the wet season

Mild drought (-1.0 < SPEI ≤ -0.5)	Moderate drought (-1.5 < SPEI ≤ -1.0)	Severe drought (-2.0 < SPEI ≤ -1.5)	Exceptional drought (SPEI ≤ -2.0)

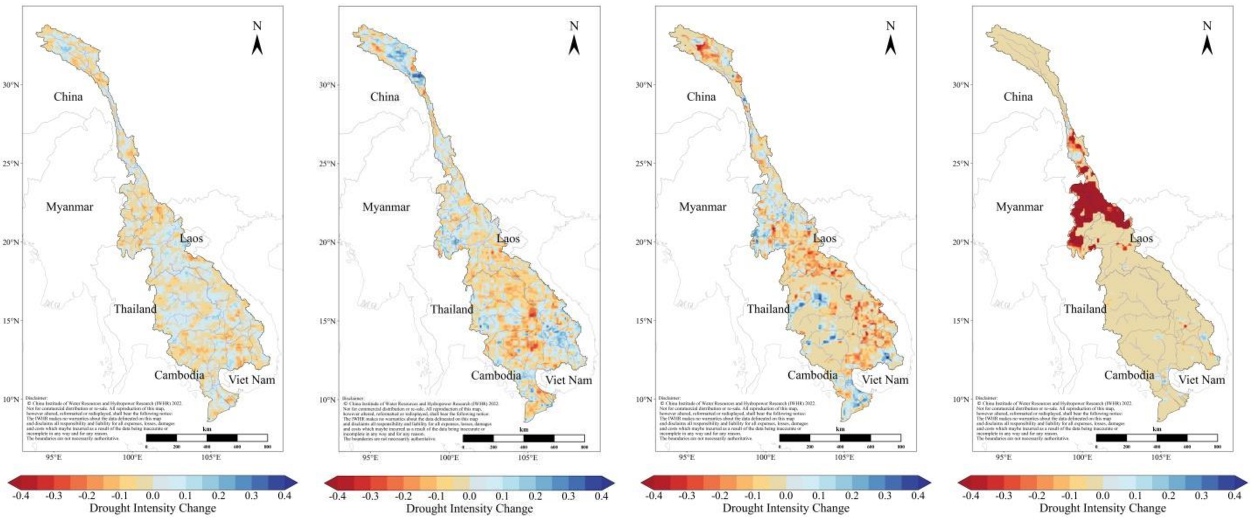


Figure N-2. Variation of wet season drought duration between 2000–2009 and 2010–2020 based on ERA5-Land dataset

ANNEX O – SPEI, PRECIPITATION AND TEMPERATURE ANOMALY FOR DROUGHT IN 2004–2005

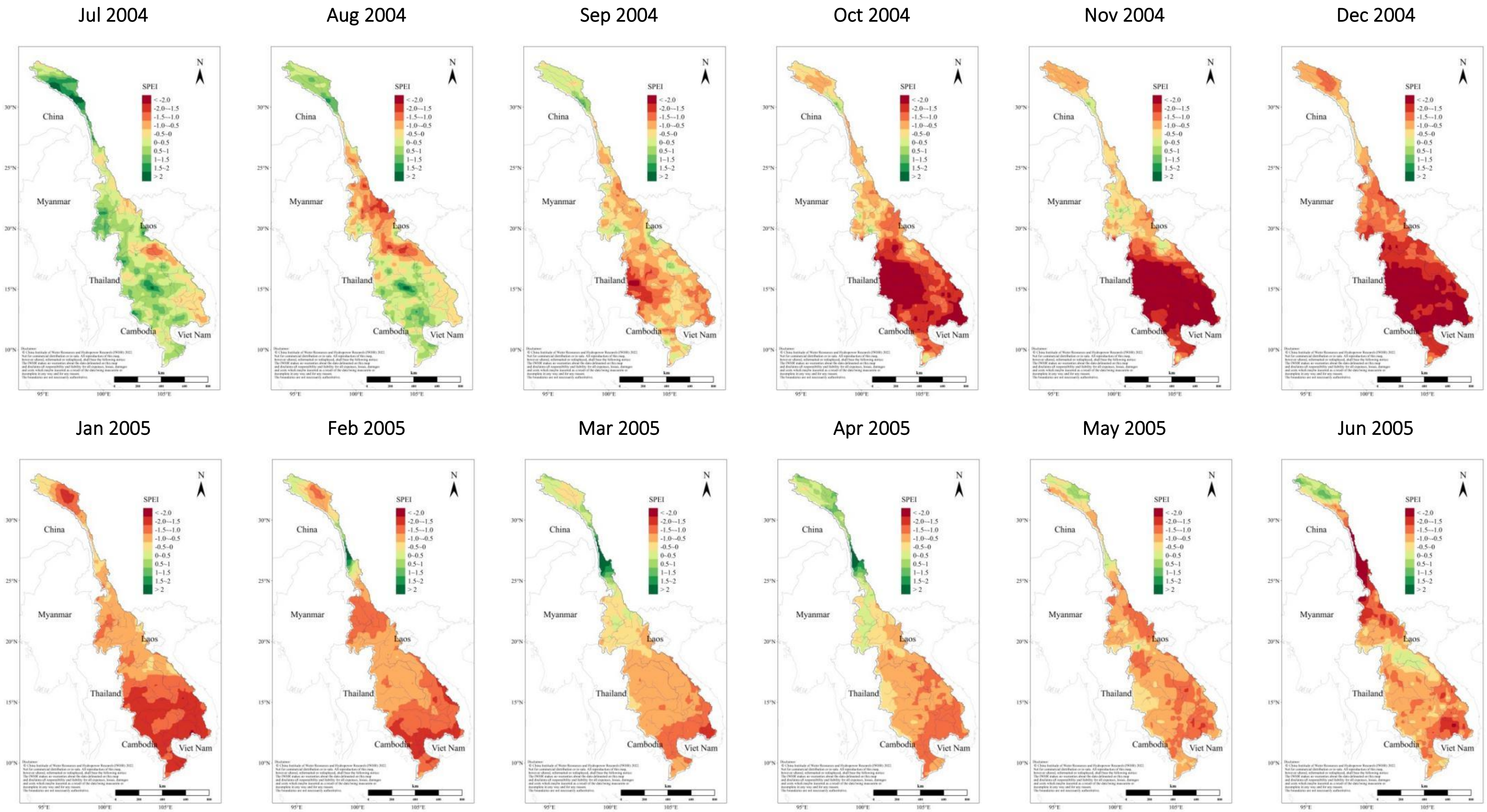


Figure O-1. Evolution of SPEI3 from July 2004 to June 2005 (based on ERA5-Land)

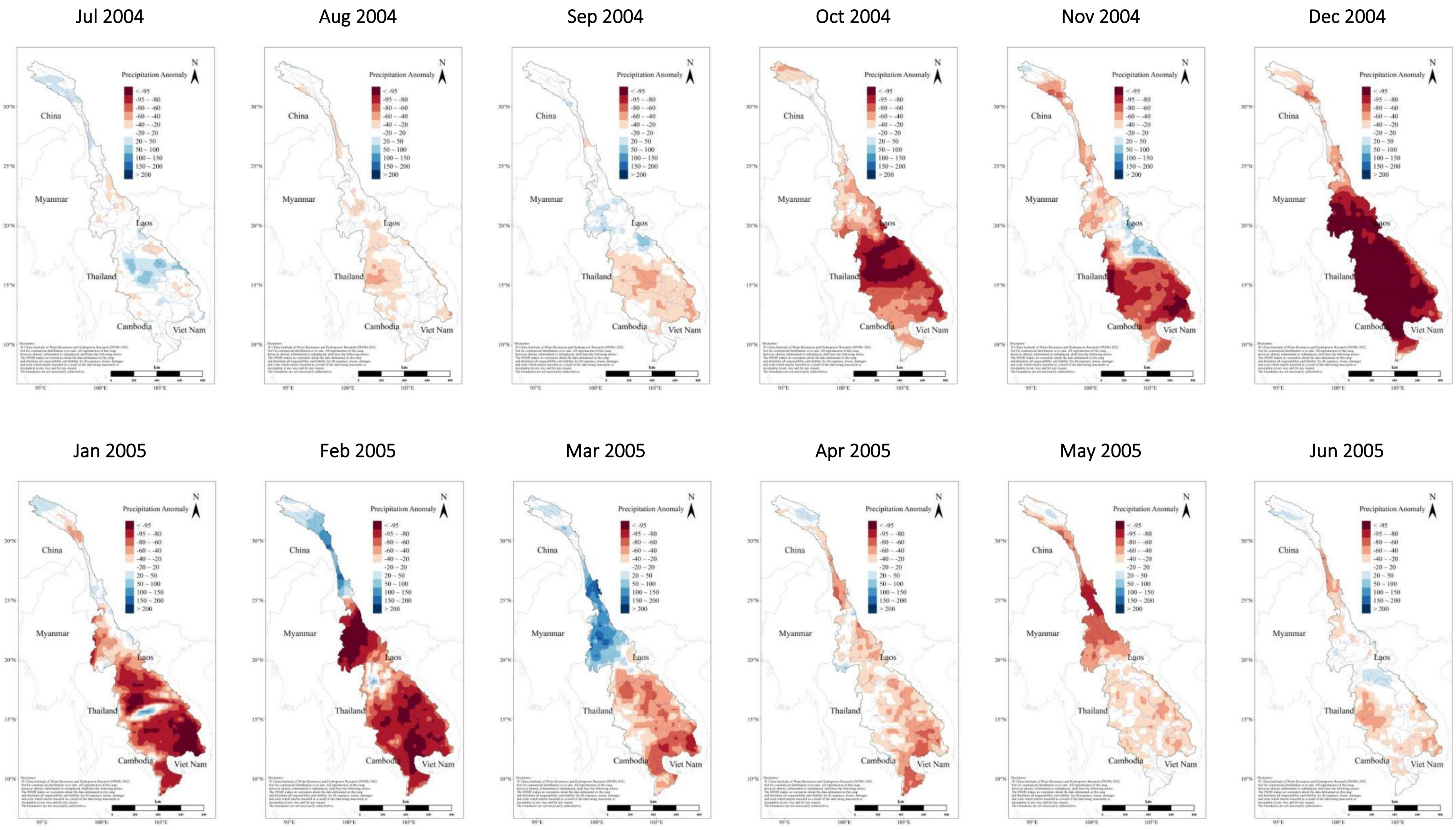


Figure O-2. Monthly precipitation anomaly of LMRB from July 2004 to June 2005 (based on ERA5-LAND data)

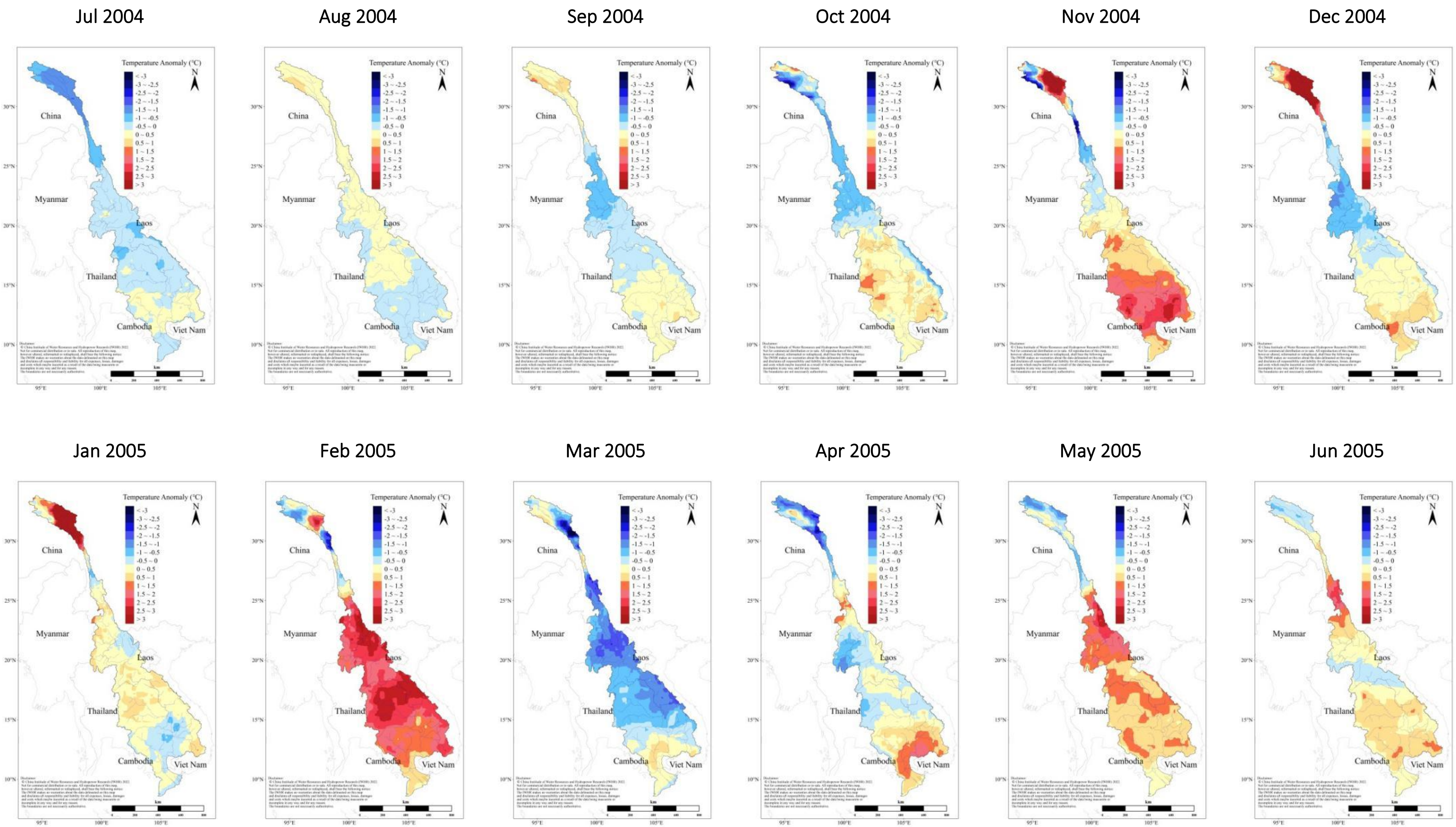


Figure O-3. Monthly temperature anomaly of LMRB from July 2004 and June 2005 (based on ERA5-LAND data)

ANNEX P – SPEI, PRECIPITATION AND TEMPERATURE ANOMALY FOR DROUGHT IN 2016

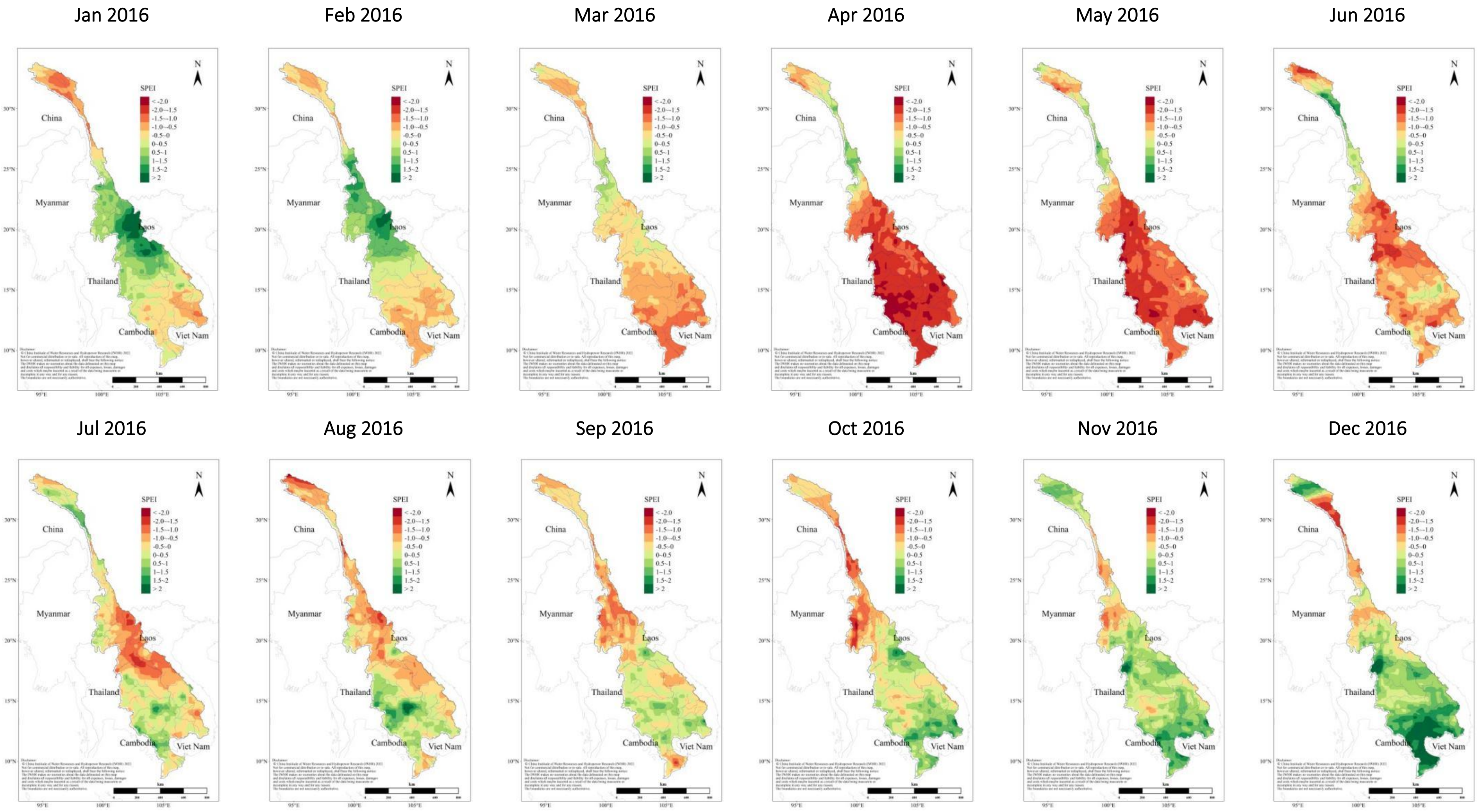


Figure P-1. Monthly SPEI3 of LMRB in 2016 (based on ERA5-LAND data)

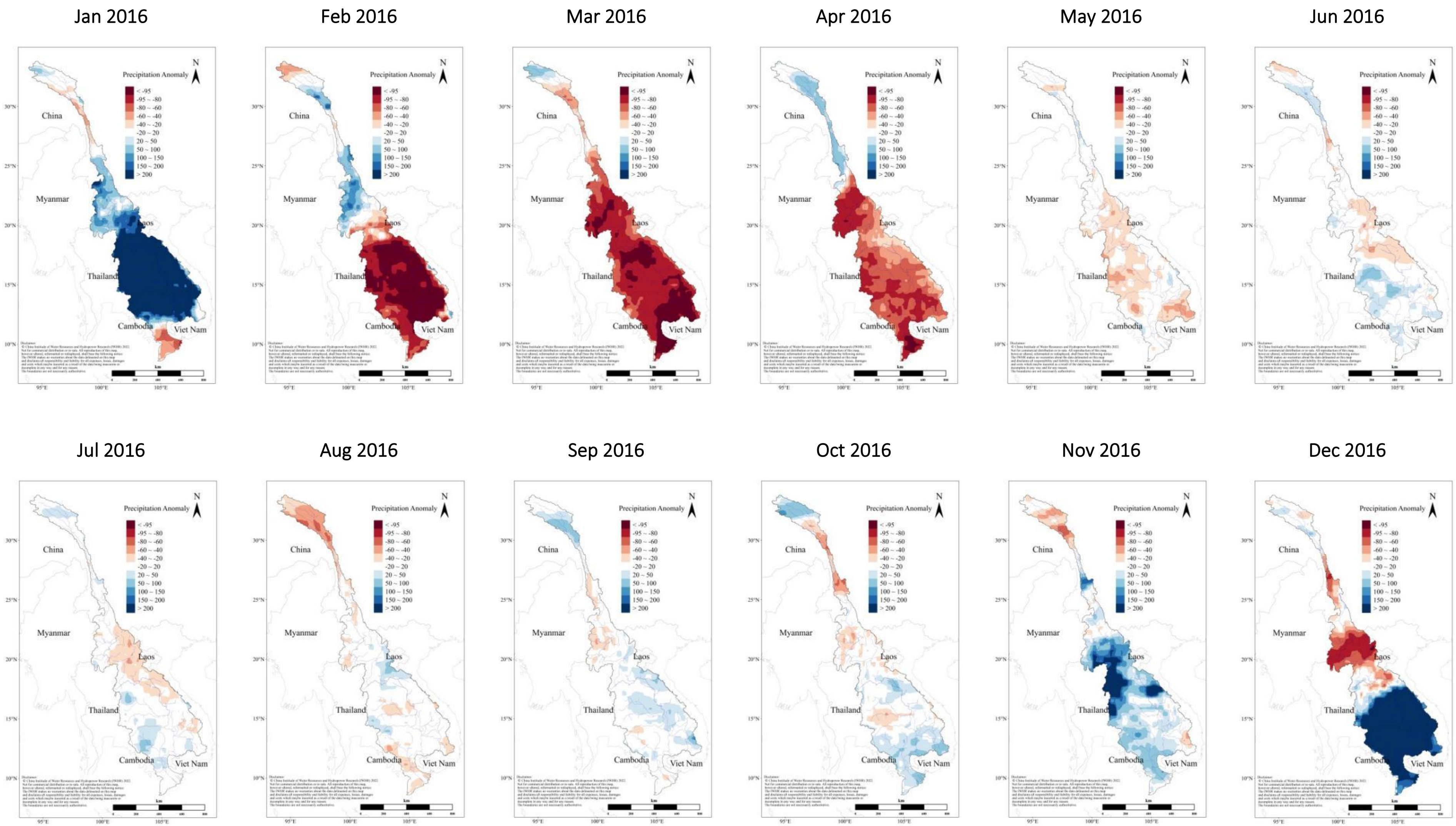


Figure P-2. Monthly precipitation anomaly of LMRB in 2016 (based on ERA5-LAND data)

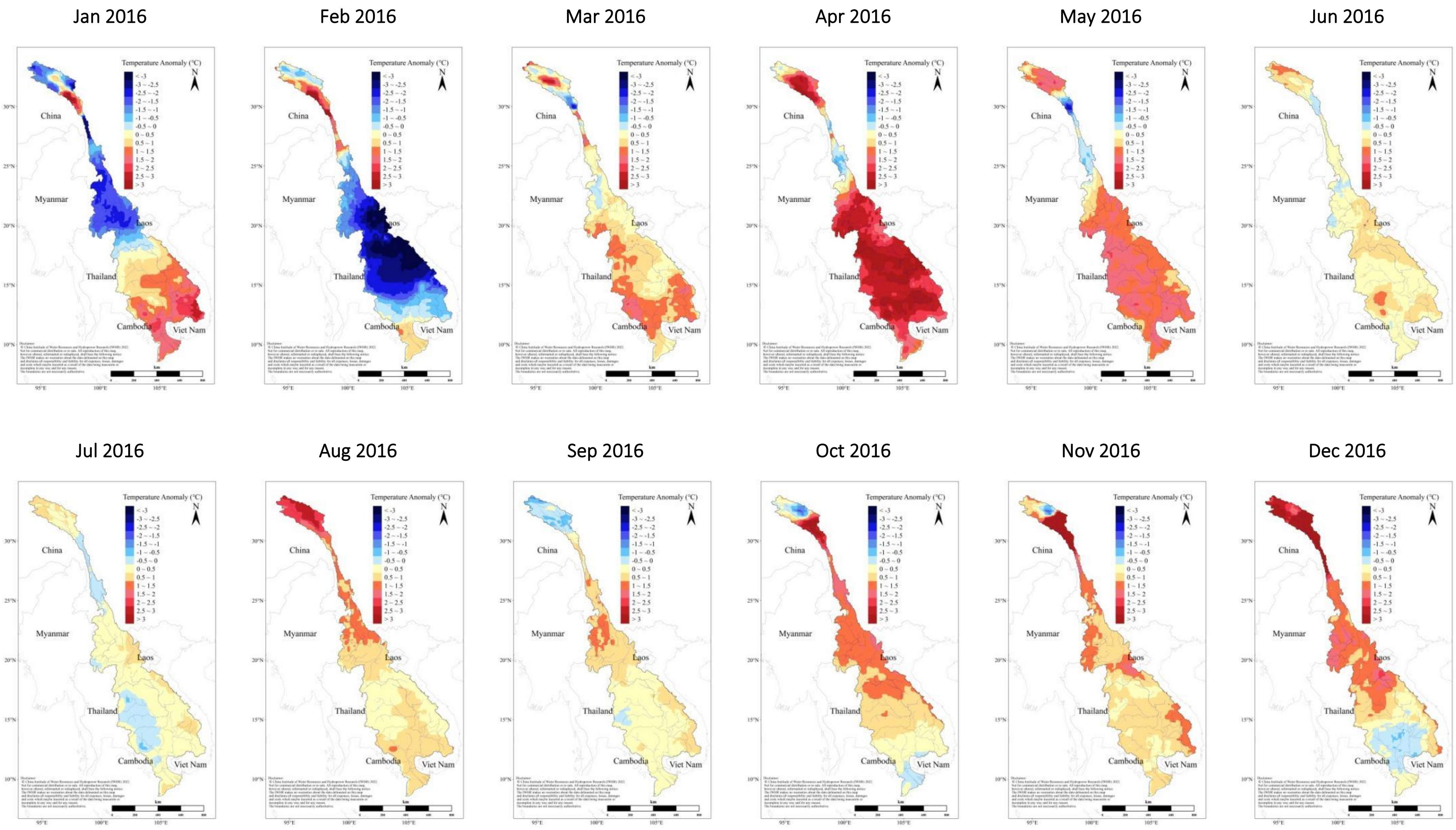
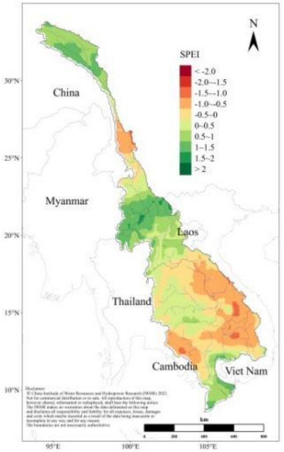


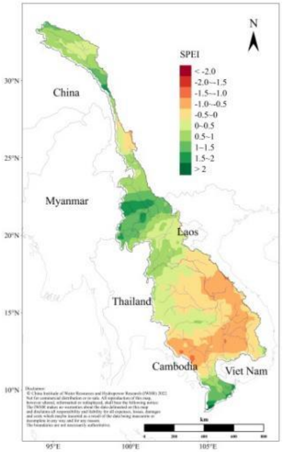
Figure P-3. Monthly temperature anomaly of LMRB in 2016 (based on ERA5-LAND data)

ANNEX Q – SPEI, PRECIPITATION AND TEMPERATURE ANOMALY FOR DROUGHT IN 2019–2020

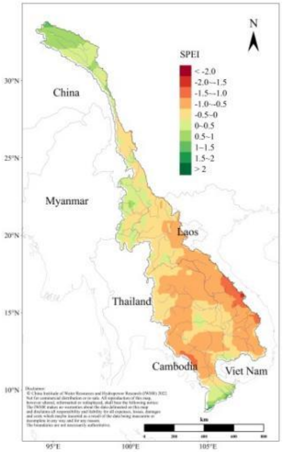
Jan 2019



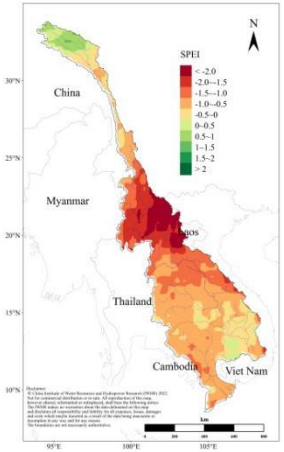
Feb 2019



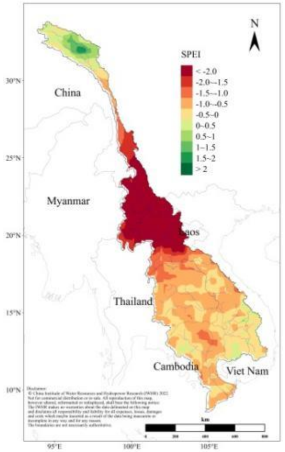
Mar 2019



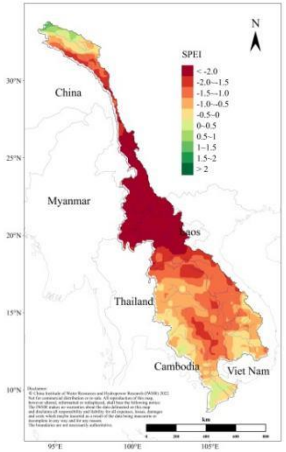
Apr 2019



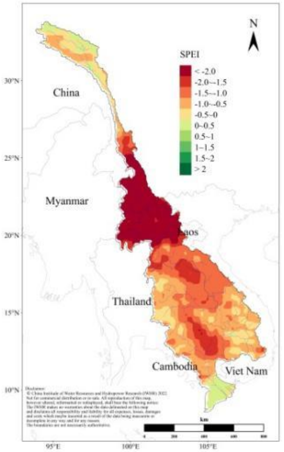
May 2019



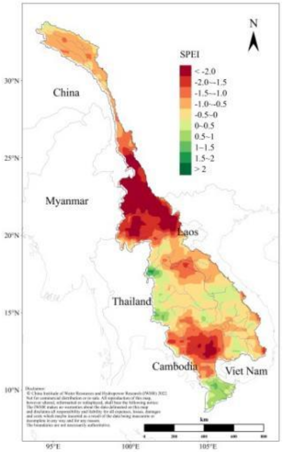
Jun 2019



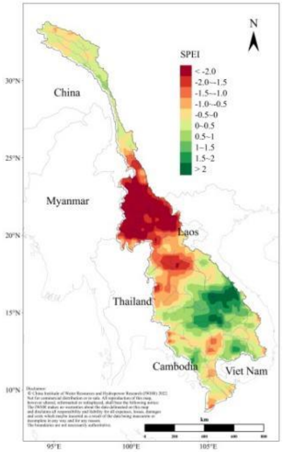
Jul 2019



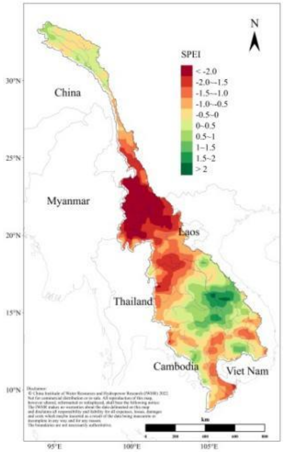
Aug 2019



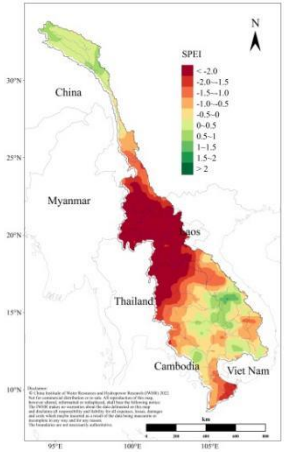
Sep 2019



Oct 2019



Nov 2019



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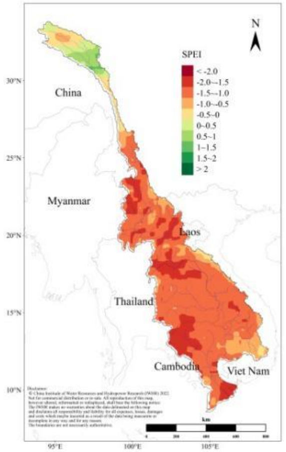


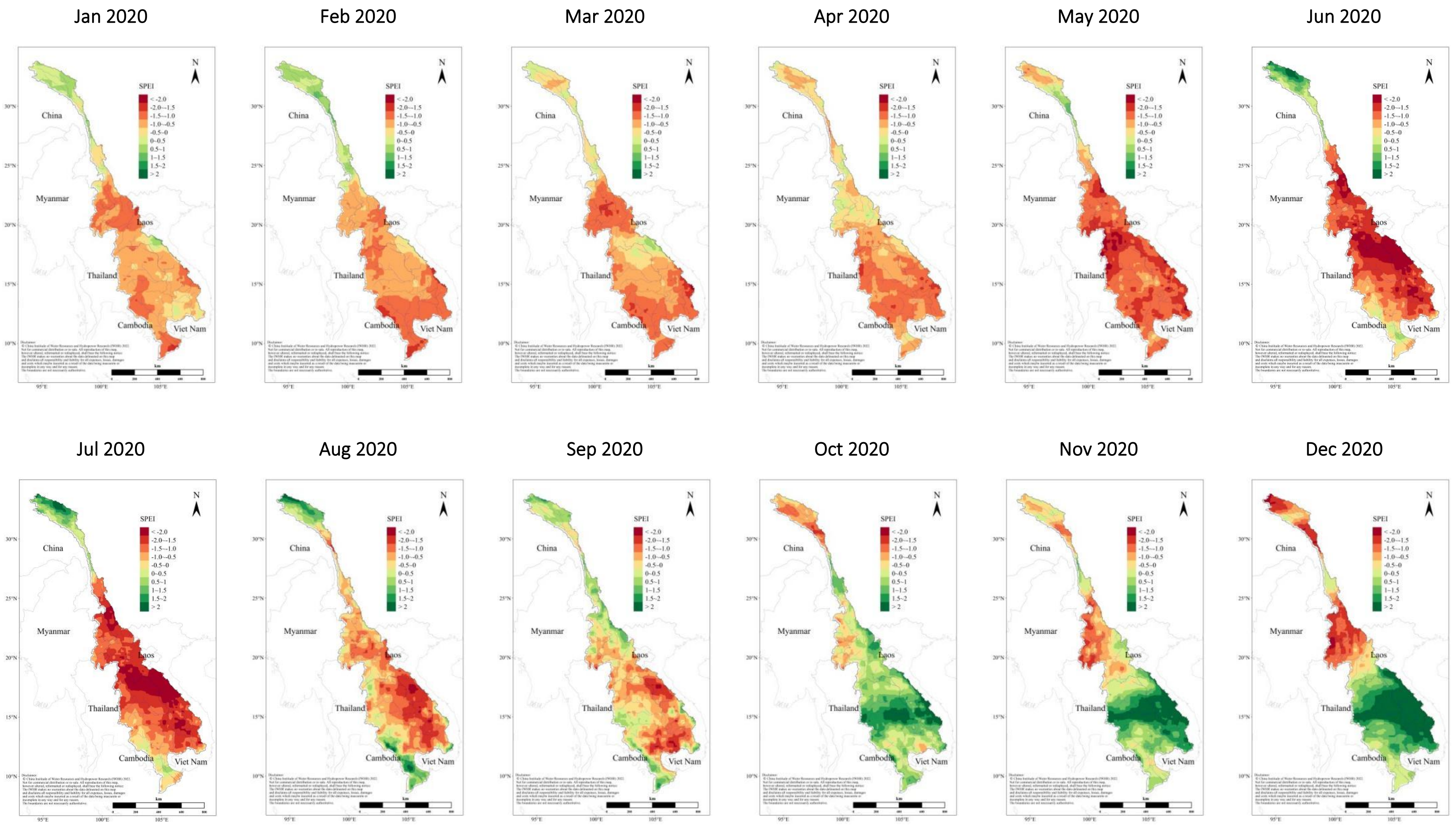
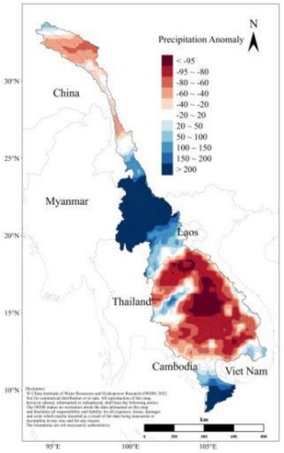
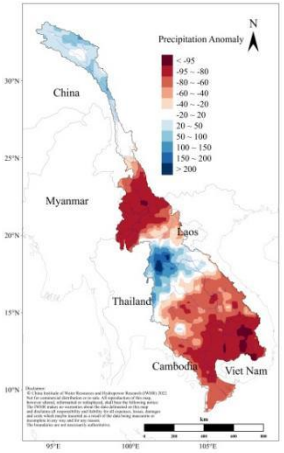


Figure Q-1. Monthly SPEI3 of LMRB in 2019–2020 (based on ERA5-LAND data)

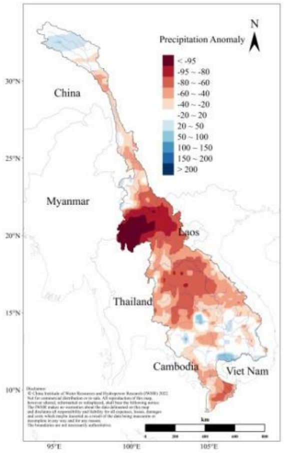
Jan 2019



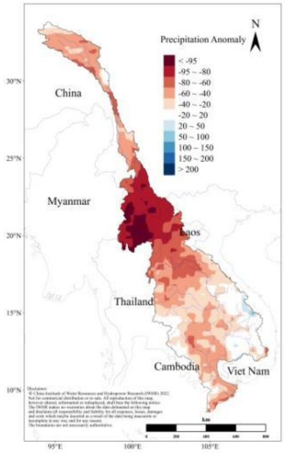
Feb 2019



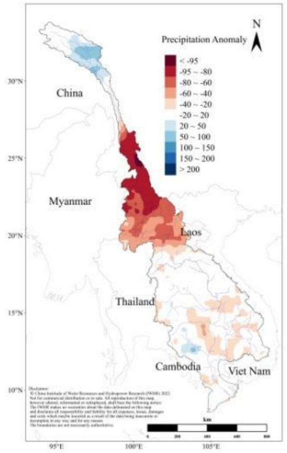
Mar 2019



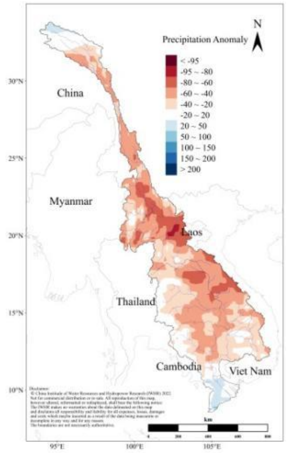
Apr 2019



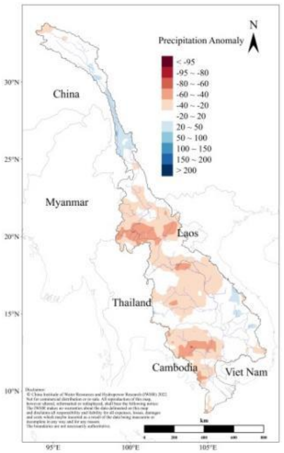
May 2019



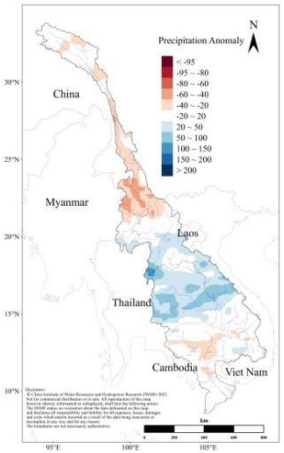
Jun 2019



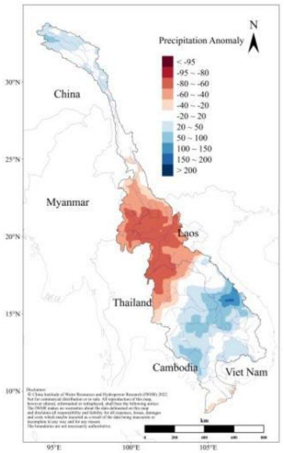
Jul 2019



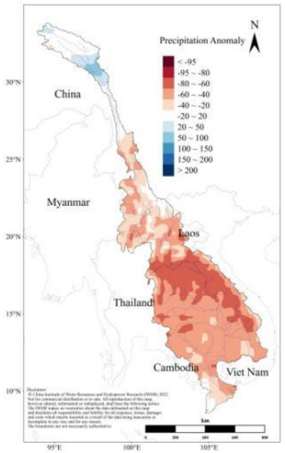
Aug 2019



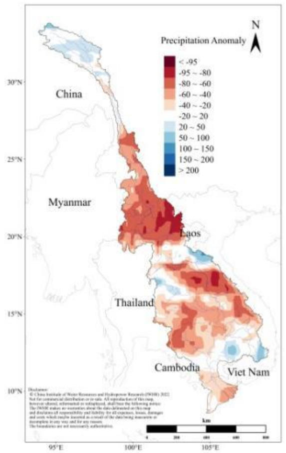
Sep 2019



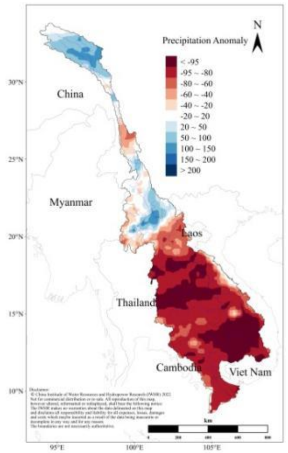
Oct 2019



Nov 2019



Dec 2019



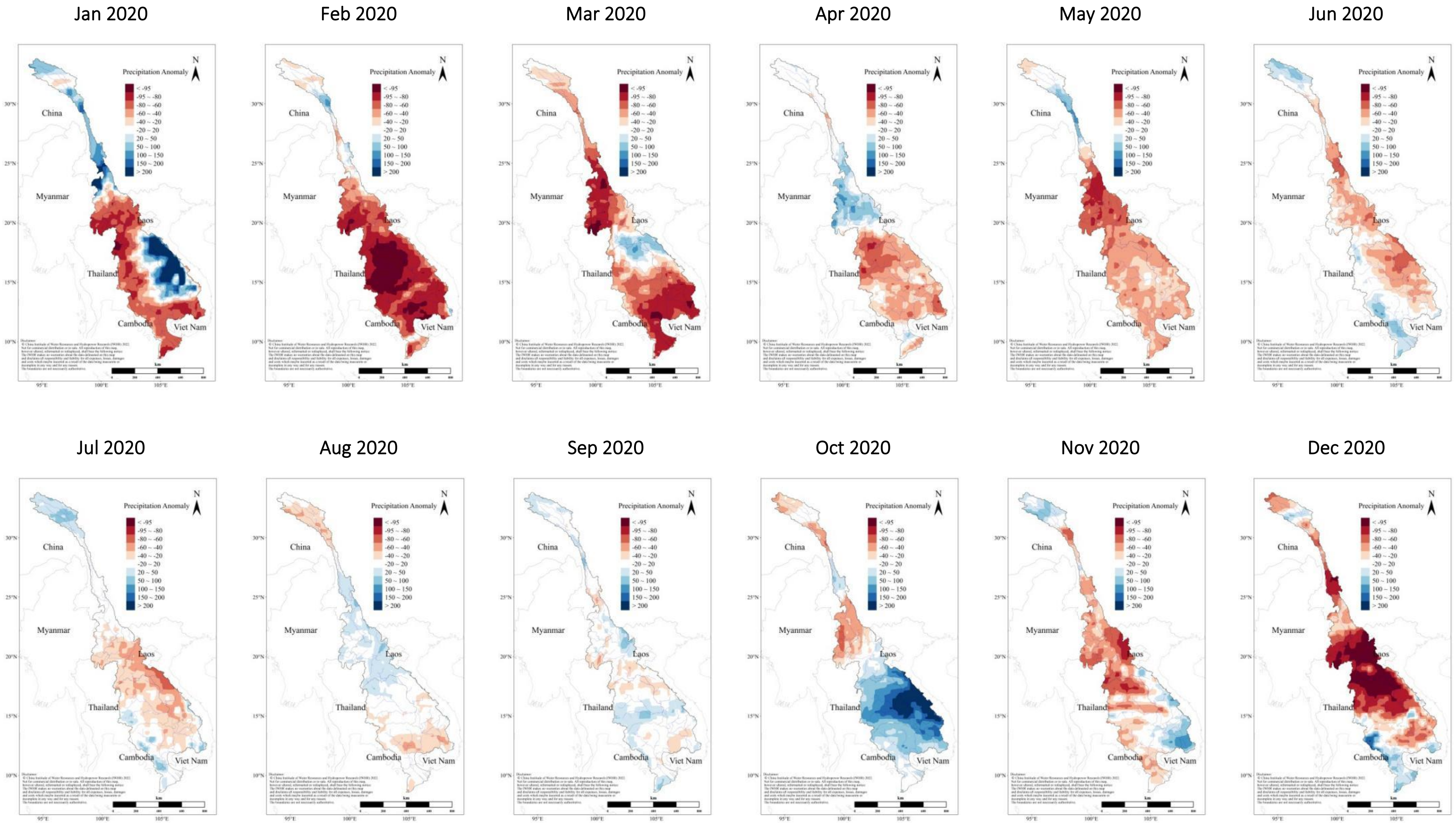
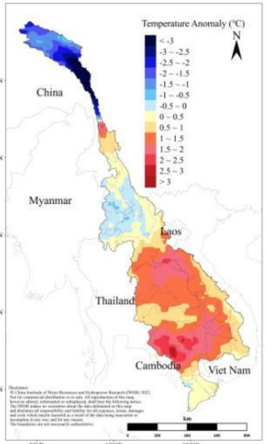
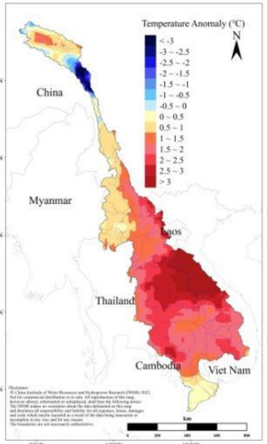


Figure Q-2. Monthly precipitation anomaly of LMRB in 2019–2020 (based on ERA5-LAND data)

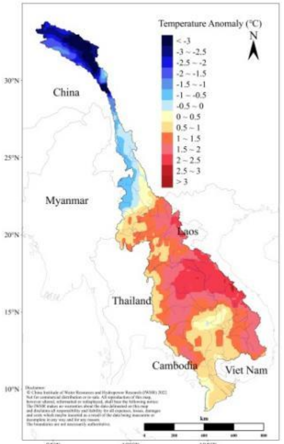
Jan 2019



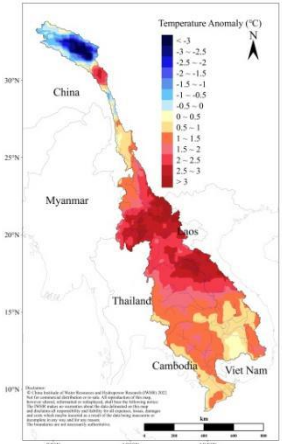
Feb 2019



Mar 2019



Apr 2019



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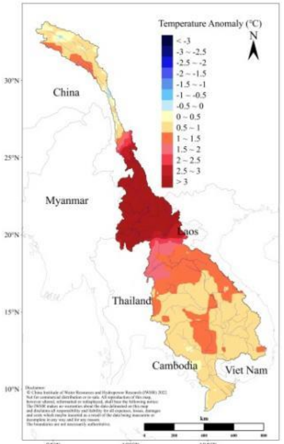
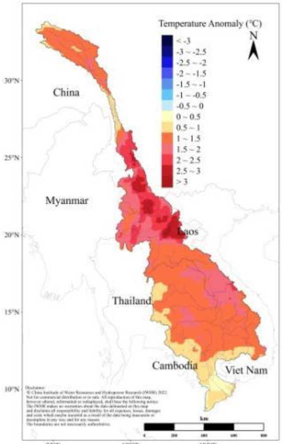
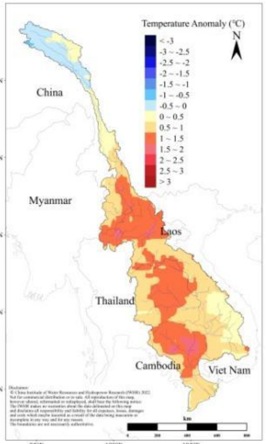


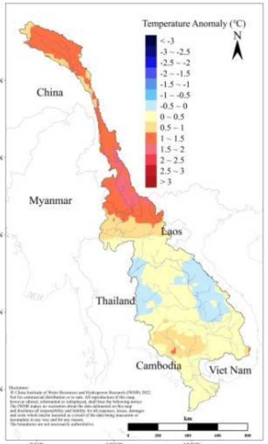
Jun 2019



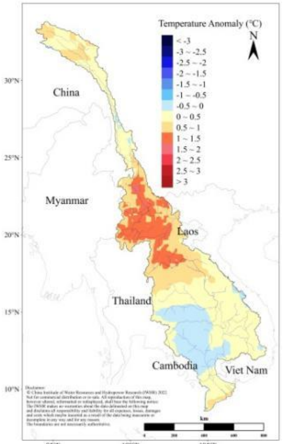
Jul 2019



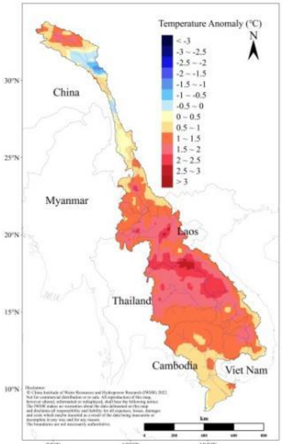
Aug 2019



Sep 2019



Oct 2019



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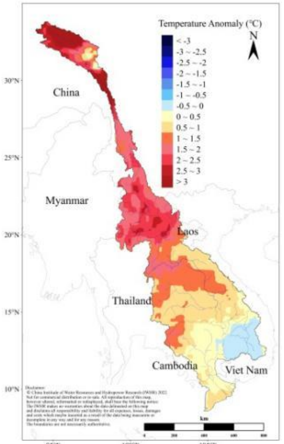

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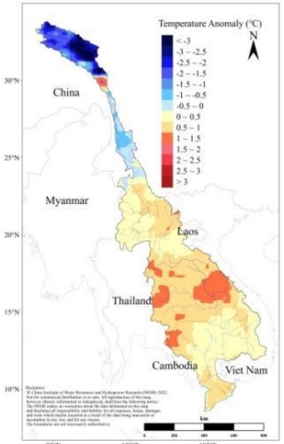

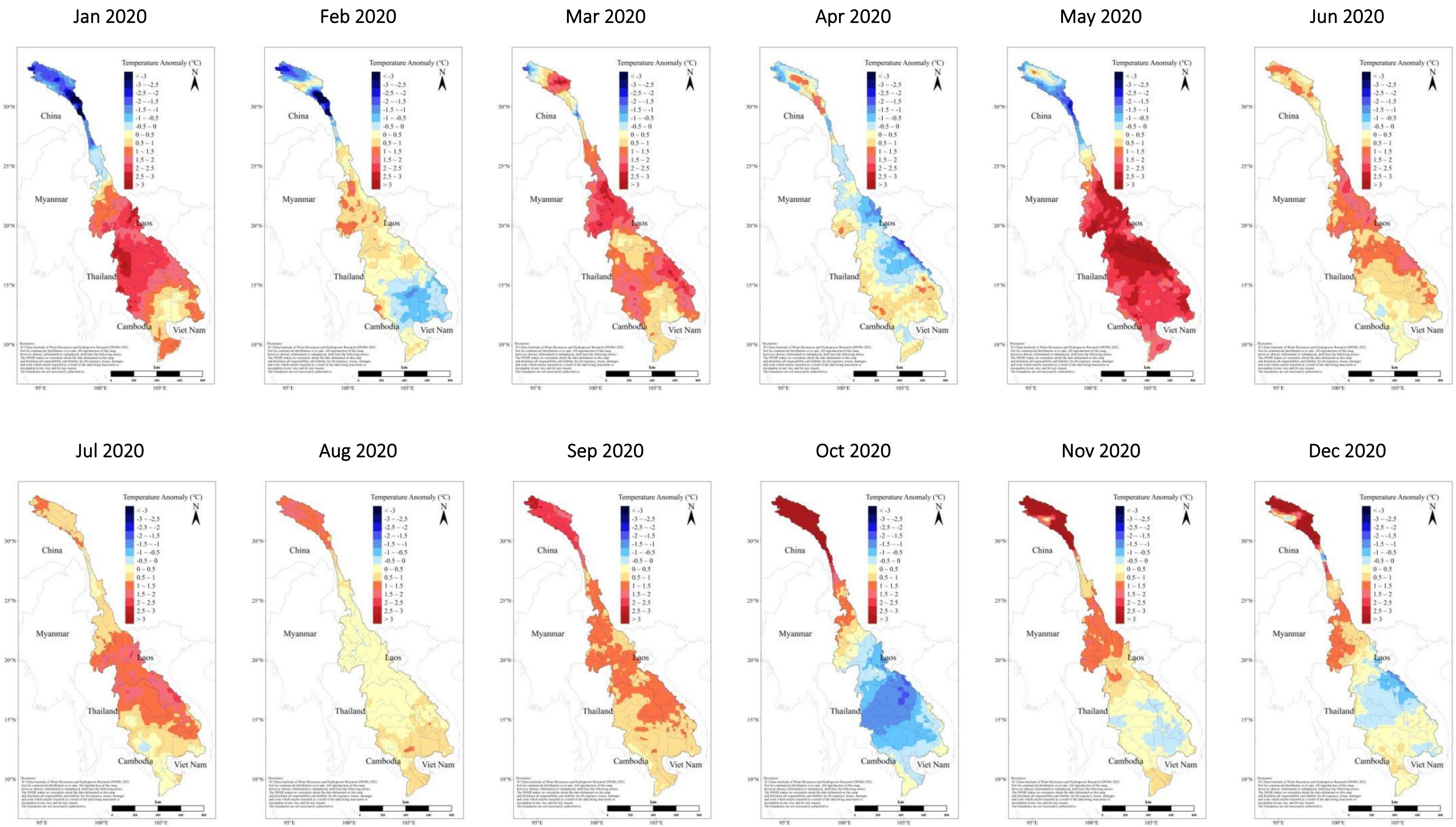

Figure Q-3. Monthly temperature anomaly of LMRB in 2019–2020 (based on ERA5-LAND data

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40,000
35,000
20,000
10,000
0
Discharge (m³/s)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
20,000
15,000
10,000
5,000
0
Annual flood peak (m³/s)
0
20
40
60
80
100
Annual flood volume (billion m³)
2010–2020
2000–2009
May
Jun
Jul
Aug
Sep
Oct