Drought Characteristics of Lancang-Mekong River Basin and the Impacts of Reservoir Regulation on Streamflow

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Executive Summary

The Lancang-Mekong River Basin (hereinafter referred to as LMRB) has been experiencing increasing frequency and intensity of drought during recent decades. Due to insufficient rainfall with abnormal monsoon and high temperature and evapotranspiration created by El Nino, the Basin witnessed a severe drought in 2019, which has attracted attention and various views from within and beyond the basin. To build knowledge and trust for further collective-action of basin-wide drought relief, this study collected hydrometeorological data covering both upstream and downstream areas and utilized state-of-the-art methods to investigate the drought characteristics and the impacts of reservoir regulation on the mainstream discharge of the Mekong River.

The objectives of this study include: (1) to investigate drought frequency and its spatiotemporal features, (2) to quantify the natural runoff composition along the mainstream of the Mekong River, (3) to investigate impacts of the regulation of Lancang cascade reservoirs on the mainstream discharge of the Mekong River.

In this study, two meteorological drought indices (SPEI and SPI) were adopted to investigate the drought characteristics in the LMRB. Two sets of long-term reanalysis dataset, i.e., CRU TS dataset from 1901 to 2019 and CHIRPS dataset from 1981 to 2019, were adopted for analysis. A distributed hydrological model (THREW) was established for the whole LMRB (above Phenom Penh). The model was run for 1991-2019 driven by gauge and remote sensing data. The gauged daily runoff data in 1991-2019 were collected from MRC and MWR of China from 8 main hydrological stations along the Lancang-Mekong River (i.e., Jinghong, Chiang Saen, Luang Prabang, Nong Khai, Nakhon Phanom, Mukdahan, Pakse, and Stung Treng).

It is found that the LMRB is experiencing high frequency of drought, and the proportion of drought occurring in the dry season is significantly higher than that in the wet season. The 2019 drought is among the most severe droughts in the past century. The regulation of reservoirs in LMRB could play an active role in dealing with droughts in the Basin. The main findings are as follows.

(1) Drought characteristics: The frequency of drought in the LMRB is high, and the average frequency of severe meteorological drought (SPEI<-1.5) is 7%. The highest

frequency of severe meteorological drought occurred in the middle and upper areas of Lancang sub-region, reaching more than 12%. The severe and exceptional droughts occurred more frequently during the recent 59 years compared to previous 60 years. Also, the proportion of drought occurring in the dry season is significantly higher than that in the wet season, which implies that the normal operation mode of reservoirs, i.e., store water in flood season and release water in dry season, is conducive to drought relief in the LMRB as a whole. For the year of 2019, the LMRB experienced one of the most severe droughts in the past century, the worst hit area was located in the region from lower Lancang to upper Mekong (Nong Khai). The 2019 drought is characterized by a long duration and severely less precipitation since the early wet season.

(2) Natural runoff composition: Lancang River contributes significantly to annual discharge at Chiang Saen, accounting for 64.4%. When it comes to the downstream of the Mekong River, the contribution rate decreases substantially, with 39.5% at Nong Khai, 24.9% at Nakhon Phanom, and 14.3% at Stung Treng. This means that the reservoirs located in the Lancang River may not supplement enough water when drought occurs in the downstream area of the Mekong River. Joint operation of all the reservoirs located in both mainstream and tributaries can be more supportive for the downstream drought relief.

(3) Impacts of reservoir regulation on the mainstream discharge: The Lancang cascade reservoirs store flood water in the rainy season and discharge more water in the dry season, which effectively increases the dry season streamflow of the Mekong River. Considering that the demand for agricultural water in the Mekong sub-region peaks in the dry season, and the drought statistically occurs more in the dry season than in the wet season, the water supplementary role of Lancang reservoir cascade can generally alleviate drought occurring in the Mekong sub-region.

Following recommendations were proposed to enhance drought relief capacity in the Basin.

(1) Integrated structural and non-structural measures to alleviate drought. Droughts occur more frequently in the dry season than in the wet season in the LMRB. As the peak of agricultural water demand of Mekong sub-region occurs in the dry season and water shortage is more likely to affect agricultural production during this period, it is recommended that holistic measures be taken to deal with the drought in the dry season.

Both structural and non-structural measures should be included, such as strengthening the construction of water storage project and supporting canal system to improve the water supply capacity, adjusting the agricultural planting structure and selecting drought-resistant crop types, promoting the drought monitoring and early warning system, developing water-saving and drought-resistant irrigation and cultivation technology.

(2) Joint operation of mainstream and tributary reservoirs for flood prevention and drought relief. According to the runoff composition analysis, the contribution rate of Lancang River to mainstream discharge decreases to 39.5% at Nong Khai, and continues to decrease to 14.3% at Stung Treng. It should be noted that the overall storage capacity of reservoirs in the tributaries of Mekong River reaches more than 37.2 billion m^3 according to the data set from CGIAR research program on Water, Land and Ecosystems, and the number will exceed 100 billion m^3 by 2030, which could play an important role of runoff regulation on the mainstream discharge of Mekong River. The drought in the LMRB is characterized by significant spatiotemporal asynchrony. It's recommended that riparian countries strengthen relevant research on joint operation of reservoirs in the upstream and downstream as well as in the mainstream and tributaries, so as to make good use of these reservoirs and provide technical support for the benefits of the whole basin.

(3) Joint research on the whole-basin flood and drought forecasting system. Strengthened cooperation is needed to cope with challenges as well as share benefits from and beyond the river. It is suggested that experts from riparian countries carry out joint research to lay a solid foundation for reciprocal cooperation mechanisms. A whole-basin flood and drought forecasting system will aid in flood prevention and drought relief, and joint research efforts are should be implemented.

Chapter 1 Introduction

1.1 Background

The Lancang-Mekong River originates from the mountains in Qinghai Province of China, flows through Tibet Autonomous Region and Yunnan Province, and flows out of China's border in Xishuangbanna Dai Autonomous Prefecture in the south of Yunnan Province. The River continues to flow through another five countries including Myanmar, Lao PDR, Thailand, Cambodia, and Viet Nam, and then enters the South China Sea in the west of Ho Chi Minh City, Viet Nam. The Lancang-Mekong River Basin (hereinafter referred to as LMRB) drains a total area of 812,400 km^2, with a total length of 4880 km, ranking the tenth in the world. The total drop of its mainstream is about 5060 m, with an average gradient of 1.04 ‰, and the average annual runoff is 475 billion m^3 (Mekong River Commission and Ministry of Water Resources of China, 2016).

In this report, the Lancang River is referred to the river course located within China and the Mekong River is referred to the course flowing through the downstream five countries. The upper reach of the Mekong River is from the border of China, Myanmar and Lao PDR to Vientiane in Lao PDR, the middle reach is from Vientiane to Pakse, the lower reach is from Pakse to Phnom Penh in Cambodia, and the delta reach from Phnom Penh to the estuary. The location of the main hydrological stations on the mainstream of the Lancang-Mekong River is shown in Figure 1, and detailed information is shown in Table 1.

In history, frequent floods and droughts have seriously threatened the LMRB and especially its downstream floodplain area. IPCC (Intergovernmental Panel on Climate Change) reports have consistently demonstrated that climate change has led to an increase of temperature globally (IPCC, 2014), which has further aggravated the frequency and severity of extreme floods and droughts. In fact, LMRB has witnessed the increasing frequency and intensity of drought events during recent decades (Tian and Liu, 2016; Guo et al., 2017), which has severely affected its water supply, irrigation, ecosystem, navigation, etc.

A recent example of severe drought occurred from the latter half of the year 2019. Gauging data from the MRC and riparian countries showed that water levels of hydrological stations on both the mainstream and tributaries of the Lancang-Mekong River have been successively lower than the long-term average in the same period of year due to the continued high temperature and low rainfall since June of 2019. Droughts have occurred in most areas on varying degrees, e.g., in some parts of Lao PDR the drought was reported to reach a 50-year intensity. Thailand and Viet Nam have also reported a continuous and severe drought, and the rainfall was significantly less in the lower part of the basin. Cambodian media reported that local governments anticipated poor harvest due to serious drought and high temperature.

It is critically important to take joint actions to alleviate severe droughts due to the transboundary nature of LMRB. According to Elinor Ostrom, building knowledge and trust are essential for solving collective-action problems (Ostrom, 2011). It should, therefore, be acknowledged that the scientific understanding of drought characteristics and the possible role of water infrastructures (i.e., reservoirs) is the very first step to building knowledge and thus the trust. This is just the purpose of this study. We collected hydrometeorological data covering both upstream and downstream areas and utilized state-of-the-art methods to investigate the drought characteristics and the impacts of reservoir regulation on the mainstream discharge of the Mekong River. We hope that this study can provide a solid basis for the physical understandings of this very important river shared by China, Myanmar, Laos, Thailand, Cambodia, and Viet Nam.

1.2 Objectives and scope

This work takes the whole LMRB as the study area and adopts the state-of-the-art methods with long-term historical data to evaluate the meteorological drought characteristics and the possible role of reservoir regulation to alleviate droughts in LMRB. Specific objectives are as follows:

(1) To investigate the drought frequency and its seasonal features by using meteorological drought indices and long-time series of meteorological data;

(2) To quantify the natural runoff composition at main hydrological stations along the mainstream of the Mekong River without impacts of reservoir regulation;

(3) To investigate the impacts of the regulation of Lancang cascade reservoirs on the mainstream discharge of the Mekong River.

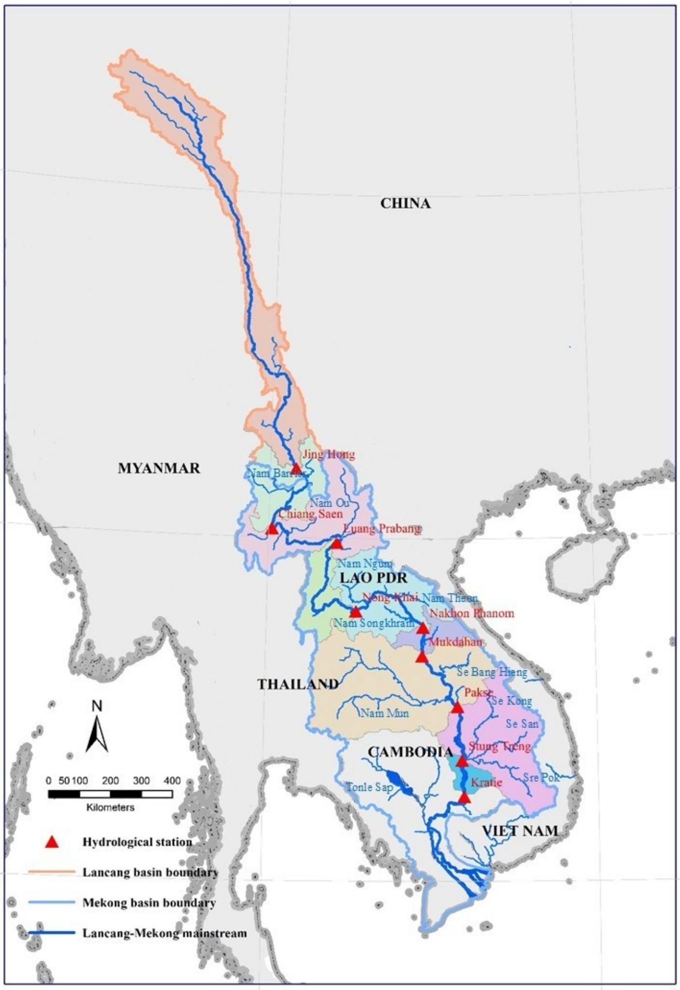

Figure 1. River network and main hydrological stations along the mainstream of the Lancang-Mekong River

Table 1. Characteristics of main hydrological stations along the mainstream of Lancang-Mekong River

River	Station	Country	Drainage area (10^4 km^2)	Distance to the estuary (km)
Lancang	Jinghong	China	14.91	2718
Mekong	Chiang Saen	Thailand	18.90	2364
	Luang Prabang	Lao PDR	26.80	2010
	Nong Khai	Thailand	30.20	1580
	Nakhon Phanom	Thailand	37.30	1221
	Mukdahan	Thailand	39.10	1128
	Pakse	Lao PDR	54.50	867
	Stung Treng	Cambodia	63.50	683

Chapter 2 Data and Methods

2.1 Overview of Methods

(1) Drought analysis: two meteorological drought indices, i.e., Standardized Precipitation Evapotranspiration Index (SPEI) and Standardized Precipitation Index (SPI), were adopted to investigate the drought characteristics in the LMRB. Two sets of long-term reanalysis dataset, i.e., Climate Research Unit gridded Time Series (CRU TS) dataset from 1901 to 2019 and Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) dataset from 1981 to 2019, were adopted for analysis.

(2) Runoff composition analysis: a distributed hydrological model (THREW) was established for the whole LMRB. The model was calibrated and verified against the observed discharge at 8 main hydrological stations along the mainstream of Lancang-Mekong River (as listed in Table 1). We chose the period of 1991-2001 to calibrate and validate the model when large dams have not been commissioned yet and a sufficient number of rain gauges are available. The parameters and construction years of major commissioned dams on the Lancang River are detailed in Table 2. According to data retrieved from MRC, the number of available rain gauges (see Figure 2 for details) became much less after 2005, so we also used satellite rainfall products (GPM IMERG) to drive the model, which is available from 2001-2019. We chose the overlap period of 2001-2005 to validate the accuracy of GPM driven simulations. The runoff compositions at 8 hydrological stations were then investigated based on the modelling results.

(3) Impacts of reservoir regulation on streamflow along the Mekong River: the natural runoff at the Chiang Saen Hydrological Station in Thailand was reconstructed by using the distributed hydrological model THREW from 1991-2019 driven by integrated rainfall time series data (rain gauge measurements and satellite rainfall product). The impacts of reservoir regulation on streamflow was then investigated by comparing the

reconstructed natural flow and observed flow at Chiang Saen Hydrological Station during different time periods. According to the construction years of major dams (in Table 2), we chose the period of 1991-2001 as a quasi-natural period without significant dam perturbation. During this period, only Manwan reservoir was commissioned in 1995 with total storage of 887 MCM (million cubic meter), which can be ignorable compared to the annual mean discharge of 56200 MCM at Jinghong (MRC and MWR of China, 2016). We then chose the period of 2010-2019 as an altered period as two major dams (Xiaowan Dam and Nuozhadu Dam) were commissioned in 2010 and 2014, respectively.

Table 2. Parameters and construction years of major dams on the Lancang River (WLE, 2018)

Project name	**Commercial Operation Date**	**Dead storage (MCM)**	**Total storage (MCM)**
Manwan	1992	630	887
Dachaoshan	2003	465	740
Jinghong	2009	810	1119
Xiaowan	2010	4750	14645
Gongguoqiao	2012	196	316
Nuozhadu	2014	10414	21749
Miaowei	2016	359	660
Huangdeng	2017	1031	1418
Wunonglong	2018	236	272
Dahuaqiao	2018	252	293
Lidi	2019	57	71

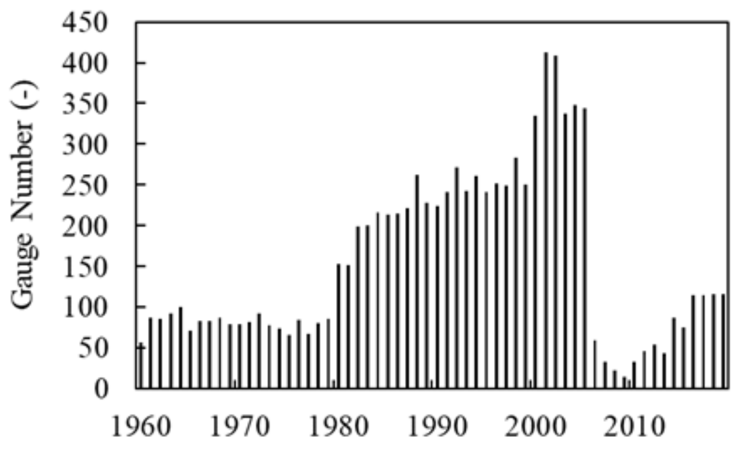

Figure 2. Number of available rain gauges from 1960 to 2019 in the Mekong River Basin

2.2 Hydrological and meteorological data

(1) Gauged rainfall and meteorological data were obtained from MRC and the China Meteorological Administration (CMA). For the Mekong sub-region, we collected daily data from 166 rain gauges and 32 meteorological gauges from 1991 to 2005 with high-quality temporal continuity. For the Lancang sub-region, we collected data from 12 rain gauges and 12 meteorological gauges with the continuous record during the same period. Meteorological data contain near-surface air pressure, air temperature, air specific humidity, wind speed and direction, sunshine duration, and solar radiation. They were used to calculate potential evapotranspiration based on the Penman-Monteith Equation, which is an important input for the THREW model.

(2) The gauged daily runoff data in 1991-2019 were collected from MRC and MWR of China for the main hydrological stations along the Lancang-Mekong River (i.e., Jinghong, Chiang Saen, Luang Prabang, Nong Khai, Nakhon Phanom, Mukdahan, Pakse, and Stung Treng).

(3) As the number of available rain gauges became significantly less after 2005, the IMERG Final Run dataset was adopted for the hydrological simulation during the recent 14 years from 2006 to 2019. IMERG is a satellite rainfall product released by GPM (Global Precipitation Measurement) project. A number of studies show that the IMERG product performs quite well in Southeast Asia (Li et al., 2019; Wang et al., 2017; He et al., 2017).

(4) The CRU TS (Climate Research Unit gridded Time Series) global reanalysis meteorological dataset and the CHIRPS (Climate Hazards Group Infrared Precipitation with Station data) precipitation dataset were 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 (except Antarctica) from 1901 to 2019. 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 119 years (1901-2019). CHIRPS precipitation dataset is jointly developed by the United States Geological Survey (USGS) and the University of California, Santa Barbara, with a sequence length of 1981 to the near present and a finer spatial resolution of 0.05°×0.05°. CHIRPS precipitation data has been successfully applied to meteorological drought analysis in the Lower Mekong Basin (Guo et al., 2017). The monthly precipitation data of CHIRPS from 1981-2019 was used in this study with the purpose of comparison with CRU TS.

2.3 Drought analysis method

(1) Meteorological drought index

In this study, two meteorological indices, the Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI), were adopted for drought analysis.

The Standardized Precipitation Index (SPI), for measuring the excess and deficit of precipitation on various temporal scales, is a widely adopted metric for drought diagnosis. The typical procedure to calculate SPI is as follows: 1) Γ distribution probability is adopted to describe precipitation in the SPI calculation; 2) Normal standardization of skewed probability distribution is conducted; 3) Drought is graded using the distribution of cumulative frequency of standardized precipitation. The SPI is an indicator expressing the precipitation occurrence probability in a given period that is applicable to meteorological drought monitoring and evaluation on or above the monthly scale. With the advantages of easy access to data, easy calculation, flexible temporal scale, and regional comparability, SPI has been widely applied to the depiction of meteorological drought in recent years. The formulae to calculate SPI are as follows (McKee et al., 1993):

$$\mathrm{SPI} = \mathrm{S}\left\{t - \frac{(c_2t+c_1)t+c_0}{[(d_3t+d_2)t+d_1]t+1.0}\right\} \qquad (1)$$

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

In specific, 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 Γ function. According to the probability density integral formula of Γ function is:

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

where, $S = 1$ when $G(x) > 0.5$, $S = -1$ when $G(x) \leq 0.5$.

The procedure for calculating the SPEI is similar to that for the SPI. However, the SPEI uses the "climatic water balance" concept, the difference between precipitation and potential evapotranspiration (P-ET_0), rather than precipitation (P) as the input (Beguería et al., 2014).

The time scale for SPI / SPEI calculation can range from 1 to 48 months or longer, expressed as SPEI 1… SPEI48（SPI1… SPI48), etc. The small scale SPEI / SPI index is used to represent the short-term drought while the longer scale index, such as SPEI12 / SPI12, reflects the inter-annual fluctuation. If the consecutive 12-month period is not significantly wet or dry, the index will be close to 0 (WMO, 2012). Considering the influence of long-term drought is more significant, the 12-month scale index (SPI12 and SPEI12) is used in the analysis of long-term drought characteristics. The 3-month index is used to analyse the characteristics of drought in a short time scale. In particular, we adopted SPEI3 and SPI3 to investigate the course of a typical drought event occurred in 2019.

Taking into consideration of the influence of evaporation on drought severity, SPEI can better reflect the impacts of drought on the hydrological system and ecosystem than SPI based on precipitation only. Therefore, this study principally adopted SPEI index to investigate the drought characteristics, which is calculated based on precipitation and potential evapotranspiration data of CRU TS from 1901-2019. At the same time, we also calculated the SPI index based on the CHIRPS data from 1981-2019 as an independent validation.

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 3. It indicates that the two grading systems have the same thresholds for moderate, severe, and exceptional droughts.

Table 3. 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, 0.0)	(-1.0, -0.5)
III	Moderate drought	(-1.5, -1.0)	(-1.5, -1.0)
IV	Severe drought	(-2.0, -1.5)	(-2.0, -1.5)
V	Exceptional drought	≤-2.0	≤-2.0

(2) Frequency of drought

In this study, we principally investigated the frequency characteristics of drought. The frequency of drought refers to the number of occurrences of drought in the entire period of time. The calculation formula is:

$$d = (n/N) \times 100\% \qquad (4)$$

where, n is the number of months drought occurs, N is the entire sequence length.

2.4 Distributed hydrological model

We adopted the THREW model (Tsinghua Hydrological Model based on Representative Elementary Watershed) to simulate the natural runoff in the LMRB.

This model was developed by Fuqiang Tian in Tsinghua University on the basis of the Representative Elementary Watershed method proposed by Murugesu Sivapalan in the University of Illinois Urbana Champaign. The important processes including glacier and snow melting were incorporated into the model to make it applicable to cold regions. The model has been successfully applied in several watersheds with different climate and landscape configurations, e.g., Illinois River Basin in the USA (Li et al., 2012; Tian et al., 2012), Lientz Basin in Austria (He et al., 2014), Hanjiang River Basin (Sun et al., 2014) and Urumqi River Basin in China (Mou et al., 2009), and Yarlung Zangbo-Brahmaputra River Basin (Xu et al., 2019).

The LMRB was divided into 595 sub-basins based on the $1 \times 1 km^2$ resolution 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 and the whole study area was finally divided into 651 representative elementary watersheds (REWs). Each of the REW was further divided into seven 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) and main channel reach zone (r-zone).

The soil hydraulic parameters were derived from the soil classification data which are extracted from the 10 km global digital soil map provided by the Food and Agriculture Organization of the United Nations (FAO). For the Leaf Area Index (LAI) data, the Normalized Difference Vegetation Index (NDVI) data, and the snow cover data, the MODIS data are used, with a spatial resolution of 500×500m, and temporal resolution of 16 days.

The daily runoff data during 1991-2001 at 8 hydrological stations along the Lancang-Mekong mainstream are used to calibrate and validate the model in a spatially distributed way. The calibration method is detailed as follows: 1) The discharge during the wet season (from June to November) and dry season (from December to May) are calibrated separately, and the simulated discharge of the two periods are then combined together; 2) The discharge at 8 stations is calibrated from upstream to downstream; 3) Once the calibration is finished at an upstream station, the parameters for the REWs draining to this station are fixed, and the discharge of the next downstream station is used to calibrate the parameters for the REWs located in the inter-region between the two stations. The whole period of 1991 to 2001 was divided into two sub-periods, which were used for model calibration (1991-1996) and validation (1997-2001) respectively. The simulation time step is daily, and the widely used model evaluation metrics (*NSE*, ln*NSE*, and *RE*) are chosen as objective functions to calibrate and validate the model, which are calculated by the following equations:

$$NSE = 1 - \frac{\sum_{n=1}^{N}(Q_o^n - Q_s^n)^2}{\sum_{n=1}^{N}(Q_o^n - \overline{Q_o^n})^2} \tag{5}$$

$$\ln NSE = 1 - \frac{\sum_{n=1}^{N}(lnQ_o^n - lnQ_s^n)^2}{\sum_{n=1}^{N}(lnQ_o^n - \overline{lnQ_o^n})^2} \tag{6}$$

$$RE = \frac{\sum_{n=1}^{N}(Q_s^n - Q_o^n)}{Q_o^n \sum_{n=1}^{N} Q_o^n} - 1 \tag{7}$$

where, *NSE* is the Nash-Sutcliffe efficiency coefficient, *RE* is the relative error, Q_o^n and Q_s^n represent respectively the observed and simulated streamflow of day *n*, and $\overline{Q_o}$ is the average of observed streamflow during the period.

Figure 3 shows the simulated and observed daily streamflow at 8 stations, and Table 4 shows the values of evaluation metrics. The *NSE* and ln*NSE* at Jinghong station during the verification period are between 0.85 and 0.9, those of the other stations are around or larger than 0.9, and *RE* are all lower than ±5%. In general, the THREW model performs quite well in simulating the streamflow in the LMRB.

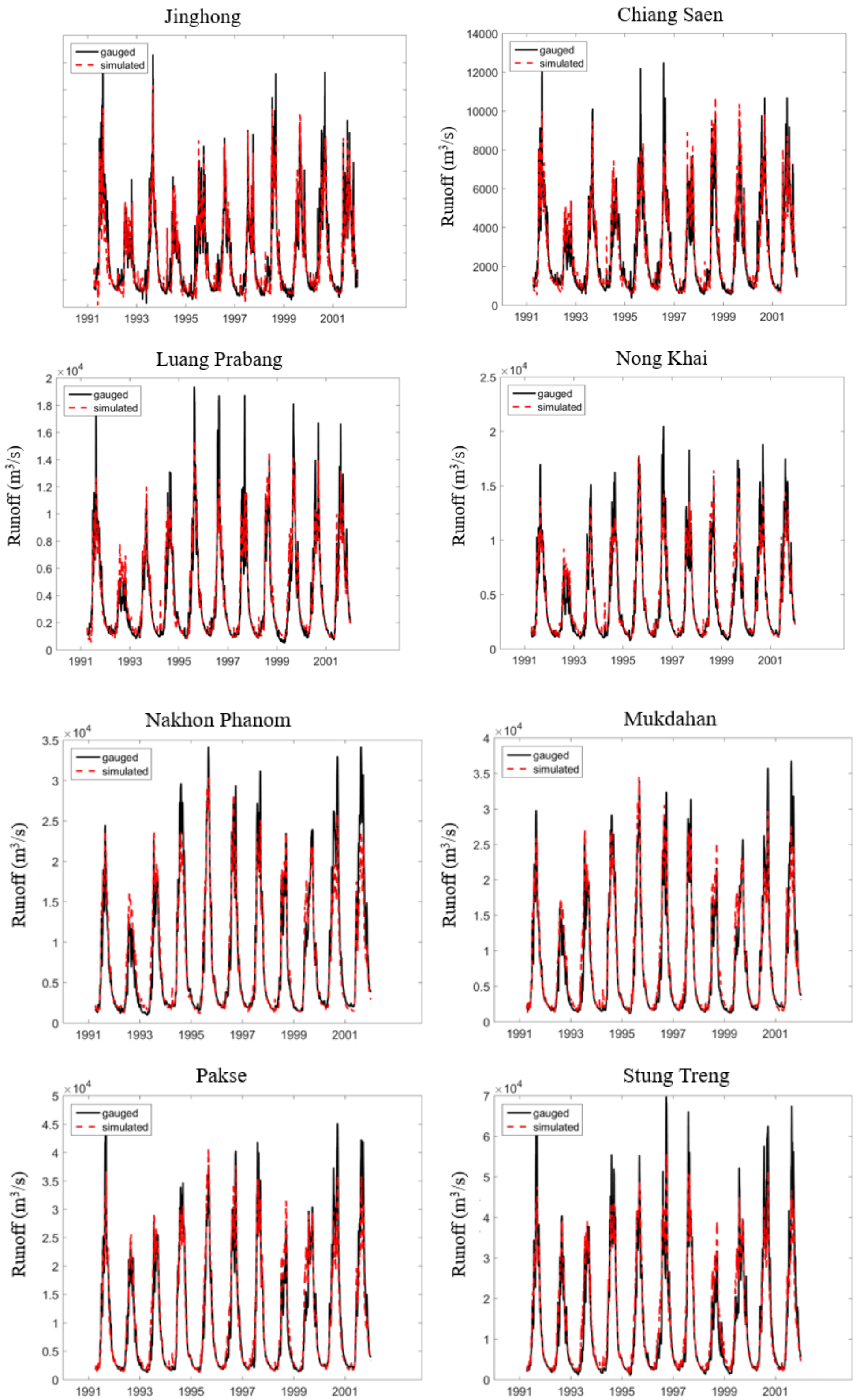

Figure 3. Simulated and observed daily streamflow at the 8 stations along the mainstream of the Lancang-Mekong River

Table 4. Evaluation metrics of THREW model simulation in the LMRB

Hydrological Gauge	**Driven by gauge rainfall data**					**Driven by IMERG rainfall data**
	Calibration (1991-1996)		**Validation (1997-2001)**		***RE***	**(2001-2005) NSE**
	NSE	**ln*NSE***	***NSE***	**ln*NSE***		
Jinghong	0.86	0.78	0.89	0.85	-3.22%	0.89
Chiang Saen	0.88	0.85	0.9	0.92	1.31%	0.95
Luang Prabang	0.88	0.89	0.92	0.94	3.21%	0.94
Nong Khai	0.92	0.93	0.92	0.95	3.23%	0.95
Nakhon Phanom	0.92	0.92	0.89	0.94	-3.57%	0.9
Mukdahan	0.94	0.93	0.93	0.95	4.92%	0.89
Pakse	0.94	0.95	0.91	0.95	0.72%	0.87
Stung Treng	0.92	0.92	0.89	0.93	2.60%	0.87
Average	0.91	0.9	0.91	0.93	-	0.91

2.5 Runoff simulation driven by IMERG rainfall product

Figure 4 shows the streamflow simulation results in 2001-2005 driven by gauge rainfall data and satellite rainfall data respectively. The last column of Table 4 shows the *NSE* calculated by the IMERG rainfall driven streamflow and gauge rainfall driven streamflow. The results indicate high accuracy of the THREW model (NSE > 0.85) driven by IMERG rainfall product. The reason we used gauge rainfall based simulation results as the reference value is that there was another dam commissioned in 2003, which could alter the streamflow to some extent (see Table 2).

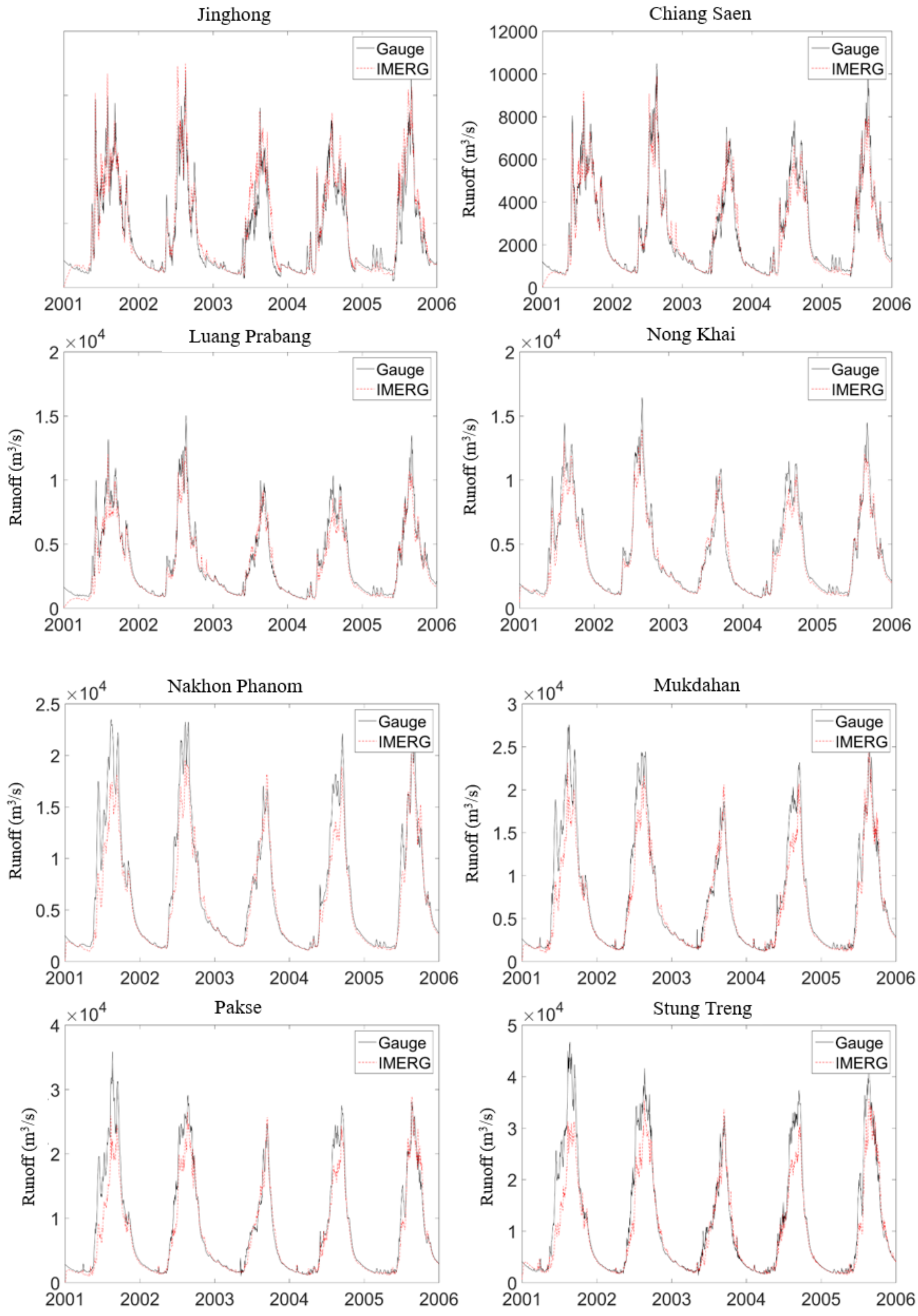

Figure 4. Streamflow simulation driven by the satellite rainfall and the gauge rainfall at 8 hydrological stations along the mainstream of Lancang-Mekong River

Chapter 3 Results

3.1 Long-term drought characteristics of the LMRB

To investigate the temporal trend of droughts, we divided the past 119 years into two periods, i.e., 1901-1960 and 1961-2019. The distribution of frequency of severe and exceptional droughts in the LMRB based on SPEI12 (SPEI <-1.5) is shown in Figure 5. The results clearly indicate that severe and exceptional droughts occurred more frequently during the recent 59 years compared to its previous 60 years, and the recent 59-year results show that drought hot spots locate principally in the middle and upper parts of the Lancang sub-region. The occurring frequency of severe and exceptional droughts in LMRB is about 7%, and it reaches about 12% in the upper and middle areas of the Lancang sub-region during the past 59 years. For the downstream part of the LMRB, about half of the area experienced an increase of severe and exceptional droughts, which are located principally in Thailand, east Cambodia, and part of Viet Nam. Conversely, most areas of Lao PDR, west part of Cambodia, and part of the Mekong Delta area experienced a decrease of severe and exceptional droughts.

Also, we calculated the occurring frequency of severe and exceptional droughts in the recent 39 years by using SPI12 based on CHIRP dataset and the result is shown in Figure 6. This result confirms Fig. 5-b, which is that of the recent 59 years. The highest frequency happens in the upper and middle areas of the Lancang sub-region.

Share of drought occurred in the dry season and the wet season is shown in Table 5. For mild and above droughts (SPEI/SPI<-0.5), the share of the dry season is slightly higher than the wet season; For moderate and above droughts (SPEI/SPI<-1), the share of the dry season is significantly higher than the wet season.

Table 5. Share of drought occurred in dry season and wet season

Drought type	Season	SPEI3	SPI3
Mild and above （SPEI/SPI<-0.5）	Dry	54%	58%
	Wet	46%	42%
Moderate and above （SPEI/SPI<-1）	Dry	62%	64%
	Wet	38%	36%

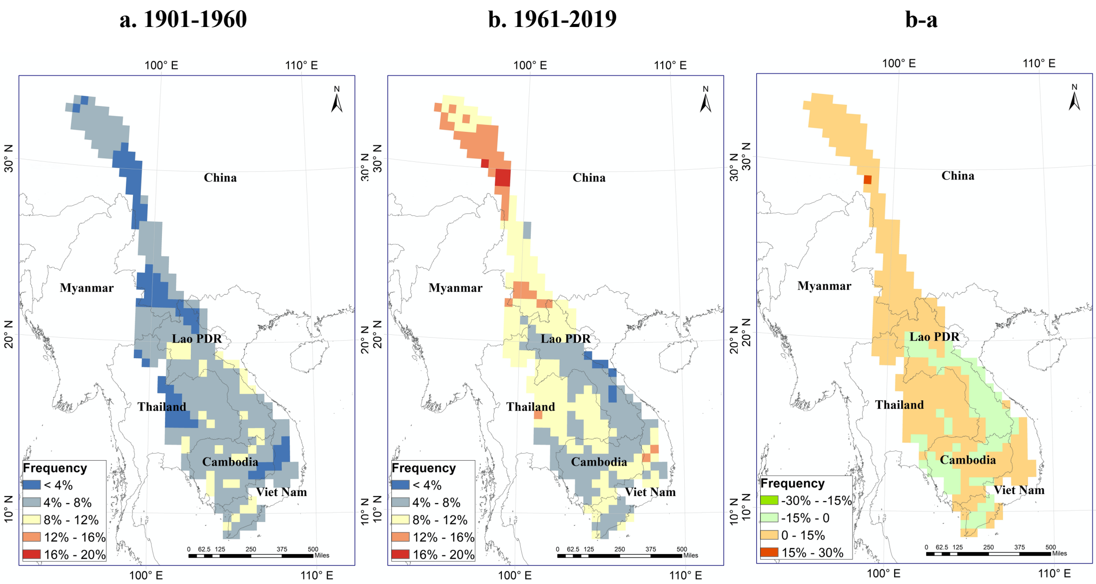

Figure 5. Frequency of severe and exceptional droughts in LMRB based on SPEI12

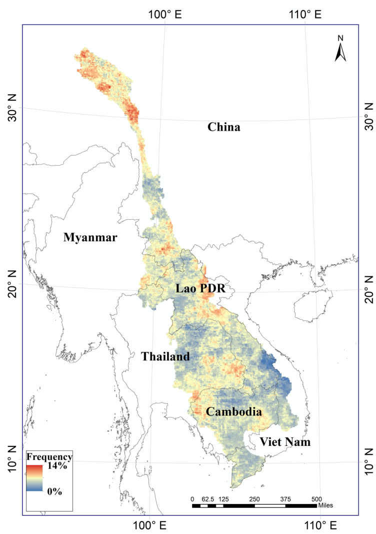

Figure 6. Frequency of severe and exceptional drought in LMRB based on SPI12 (1981-2019)

3.2 2019 drought event

According to the meteorological data provided by CMA, the annual precipitation of 2019 in the Lancang River basin is 680.4mm, which is about 25% less than its long-term average, with that of April to June is 40% to 70%. 'Weekly Flood Situation Report for the Mekong River Basin' published by MRC shows that most parts of the river basin experienced drought and less rainfall from May 2019. The precipitation from June to October recorded in Chiang Sean, Luang Prabang, Nong Khai stations were 40%, 50%, and 20% less than the last few years respectively (MRC, 2019). In addition, the mainstream of Mekong River experienced the lowest water level from July to November compared with the same period in history.

Above descriptions can be confirmed by our analysis. Annual scale (12 months) of SPEI and SPI results both indicate that 2019 and 2015 are the most severe drought years in history, as shown in Figure 7.

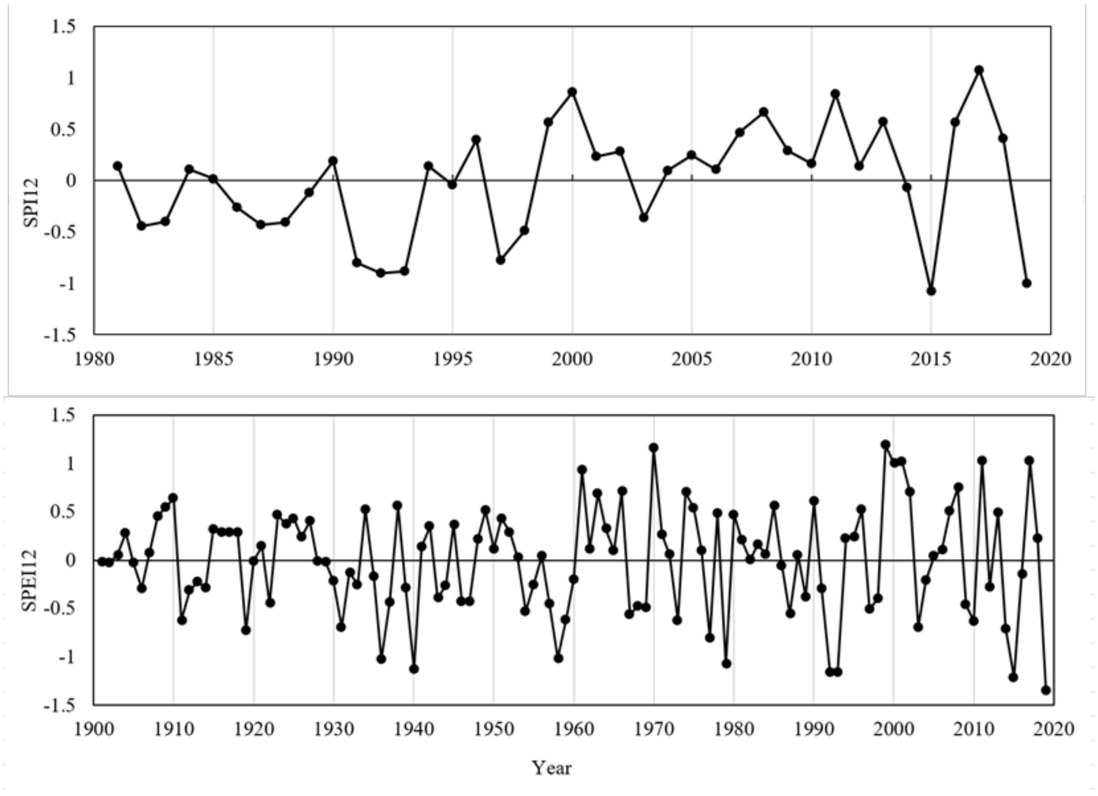

Figure 7. Dynamics of SPI12 (1981-2019) and SPEI12 (1901-2019) of the LMRB

The monthly SPEI3 and SPI3 sequence of Lancang River Basin and LMRB are shown in Figure 8. For the whole basin, the drought began in March 2019 and lasted until the end of the year. For the Lancang River Basin, the drought began in April and reached its peak in June. The severity of drought in Lancang River Basin was even more serious compared to the whole basin during the months of June and August based on SPEI index. However, the drought in the Lancang sub-region was relieved from September in 2019.

The monthly meteorological drought indices of LMRB in 2019 is shown in Figure 9 and Figure 10. It can be seen from the figures that the spatial distribution of SPEI3 and SPI3 has a good consistency, both indicating that serious drought began in April 2019 in the basin, and the drought hot spot is located from the lower reaches of Lancang River to the upper reaches of Mekong River (Nong Khai). The drought in Thailand on the western edge of the basin lasted for 12 months.

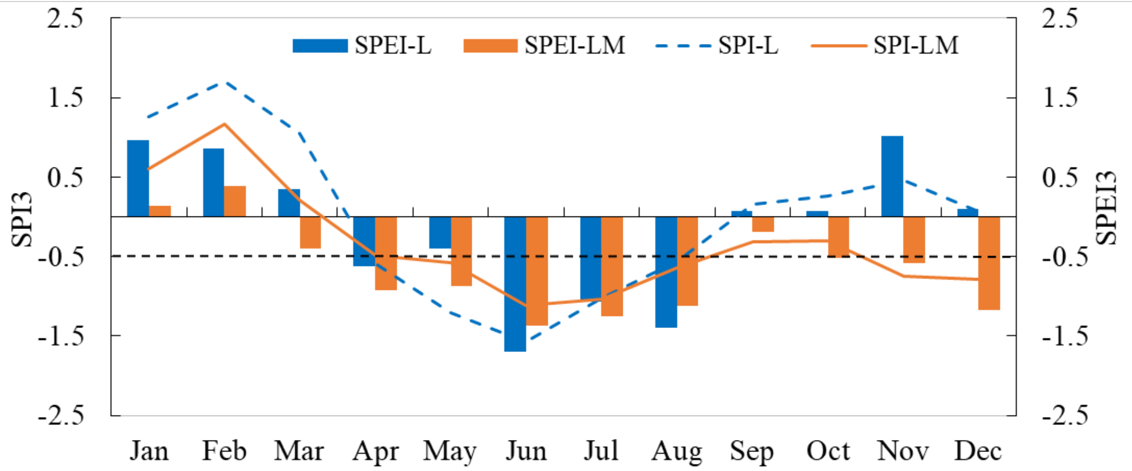

Figure 8. Drought index sequence of 2019 (L is Lancang River Basin; LM is LMRB)

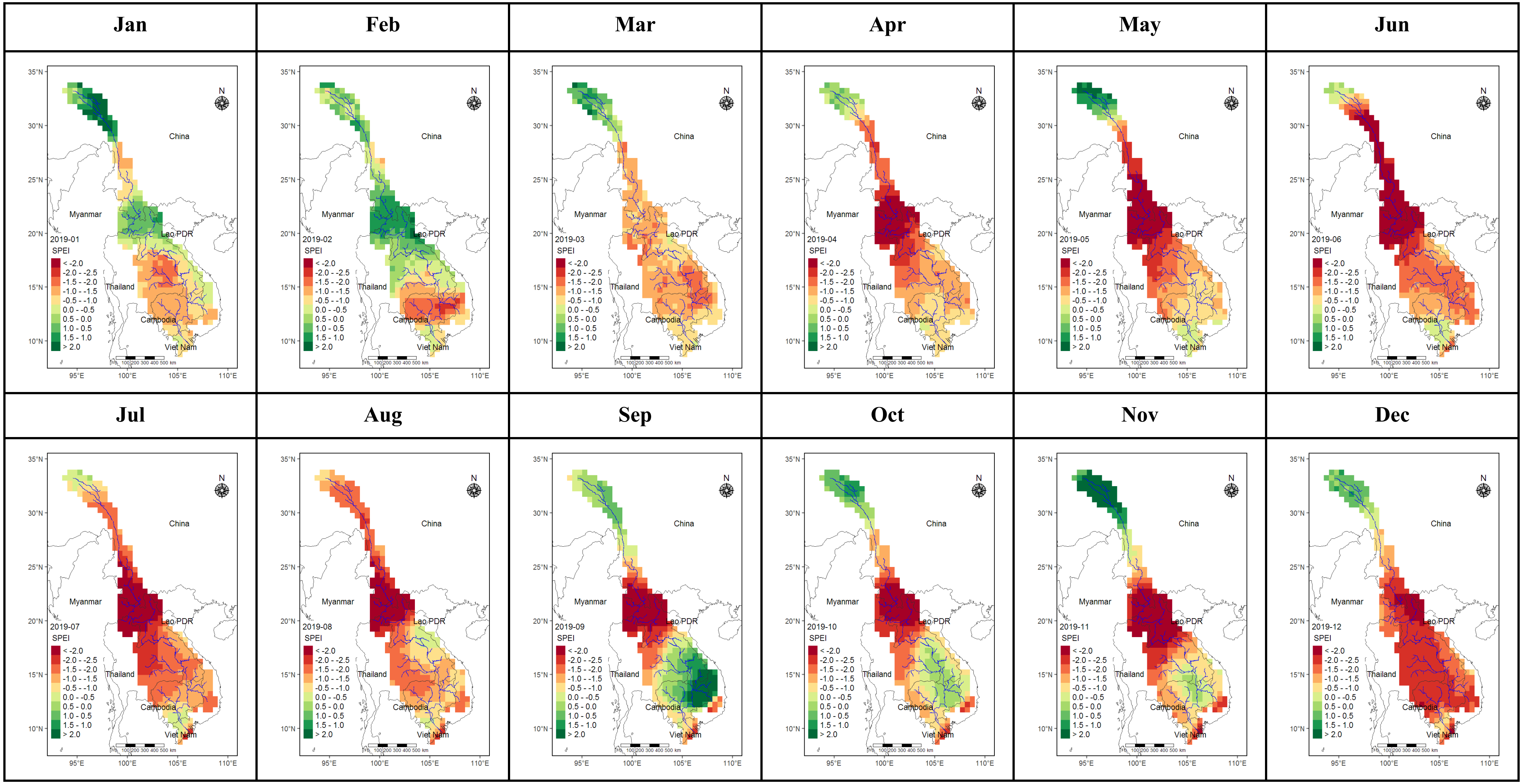

Figure 9. Monthly SPEI3 of LMRB in 2019 (based on CRU TS data).

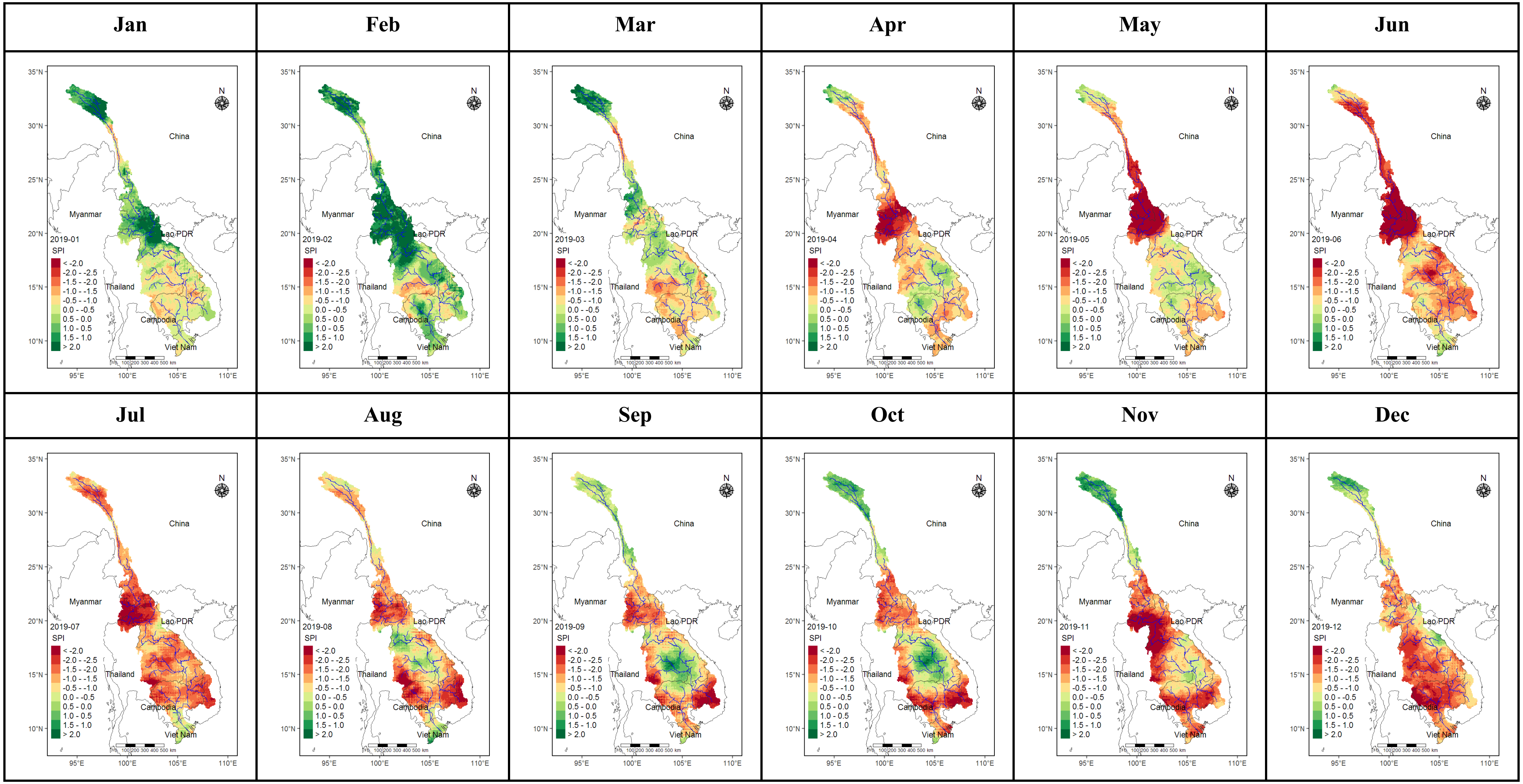

Figure 10. Monthly SPI3 of LMRB in 2019 (based on CHIRPS data).

3.3 Natural Runoff composition of discharge along the Mekong River

Natural runoff was simulated from 1991 to 2019 based on the THREW model driven by gauge rainfall and satellite rainfall dataset, which is then used to calculate the contribution ratios of Lancang River and other 12 tributaries to annual runoff volume at 8 hydrological stations along the Mekong River. The results are listed in Table 6 and in Figure 11. Not surprisingly, the contribution ratio from Lancang River shows a decreasing trend with the increase of river distance. The ratio is 64.4% at Chiang Saen (354 km from Jinghong), 24.9% in Nakhon Phanom (1497 km from Jinghong), and 14.3% in Stung Treng (1851 km from Jinghong). At Stung Treng Hydrological Station, the main tributaries contribute substantial water volume to the mainstream include Se Kong, Nam Ngum, Nam Mun, Se San, and Sre Pok. To be noted, the contribution ratios we obtained based on the distributed hydrological model are similar to the reported values by MRC as listed in Table 6 (MRC, 2007).

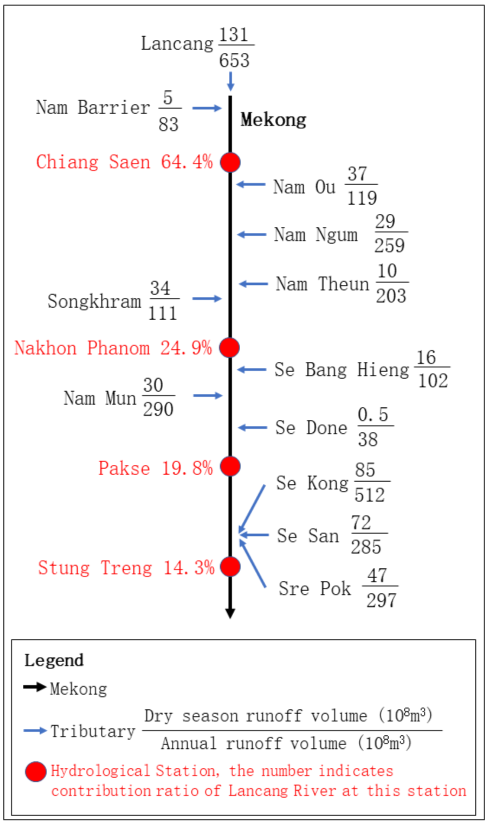

Figure 11. Runoff volume from major tributaries and contribution ratio of Lancang River

Table 6. Contribution ratio (%) of major tributaries to annual runoff at eight hydrological stations along the Mekong River (1991-2019)

Contributing tributary / **Hydrological station**	**Lancang**	**Nam Barrier**	**Nam Ou**	**Nam Ngum**	**Nam Theun**	**Nam Songkhram**	**Se Bang Hieng**	**Se Done**	**Nam Mun**	**Se San**	**Se Kong**	**Sre Pok**
Chiang Saen	64.4	8.6	-	-	-	-	-	-	-	-	-	-
Luang Prabang	45.2	6.0	8.1	-	-	-	-	-	-	-	-	-
Nong Khai	39.5	5.3	7.1	-	-	-	-	-	-	-	-	-
Nakhon Phanom	24.9	3.3	4.5	8.2	6.9	4.8	-	-	-	-	-	-
Mukdahan	22.9	3.0	4.2	7.5	6.3	4.4	-	-	-	-	-	-
Pakse	19.8	2.6	3.6	6.4	5.4	3.8	2.6	0.9	6.8	-	-	-
Stung Treng	14.3	1.9	2.6	4.6	3.9	2.7	1.9	0.7	4.9	5.8	8.9	6.7
Kratie	13.8	1.8	2.5	4.5	3.8	2.6	1.8	0.7	4.7	5.6	8.6	6.5
Contribute ratio (%) at Kraite reported by MRC	16.5	-	3.1	4.9	5.7	2.4	3.4	1.4	5.6	4.0	8.2	6.6

* Runoff from Lancang River means the discharge at Jinghong Station

3.4 Impacts of reservoir regulation on mainstream discharge

Table 7 presents the simulated annual runoff volume at Stung Treng Hydrological Station from 2001 to 2019 driven by IMERG rainfall data. The result shows that the year 2019 witnessed the lowest runoff volume since 2001, which means the most severe hydrological drought year during the recent 19 years. This partly confirms the conclusion obtained from long-term drought analysis.

Figure 12 shows the natural (simulated) and observed regime curve (average monthly runoff volume) at Chiang Saen Hydrological Station during 2001-2019. As one of the largest dams, Xiaowan dam, put into operation in 2010, two time periods are defined to investigate the impacts of reservoir regulation on the streamflow, i.e., 2001-2009 and 2010-2019. The natural and observed regime curves for 2001-2009 are almost identical, which means the hydrological model performs well under no reservoir condition. Also, the nature and observed regime curves during 2010-2019 clearly shows that reservoir operation reduces the runoff during the rainy season and supplement the runoff during the dry season.

Table 7. Annual precipitation and simulated runoff at Stung Treng from 2001 to 2019

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Runoff (billion m^3)	325.1	338.7	273.5	282.8	313.8	341.1	312.2	292.4	286.5	278.1
Precipitation (mm)	1732	1676	1494	1528	1617	1681	1653	1716	1540	1489
Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	
Runoff (billion m^3)	368.8	277.5	317.5	324.0	274.3	285.2	334.0	346.0	262.5	
Precipitation (mm)	1775	1540	1712	1568	1424	1650	1753	1710	1010	

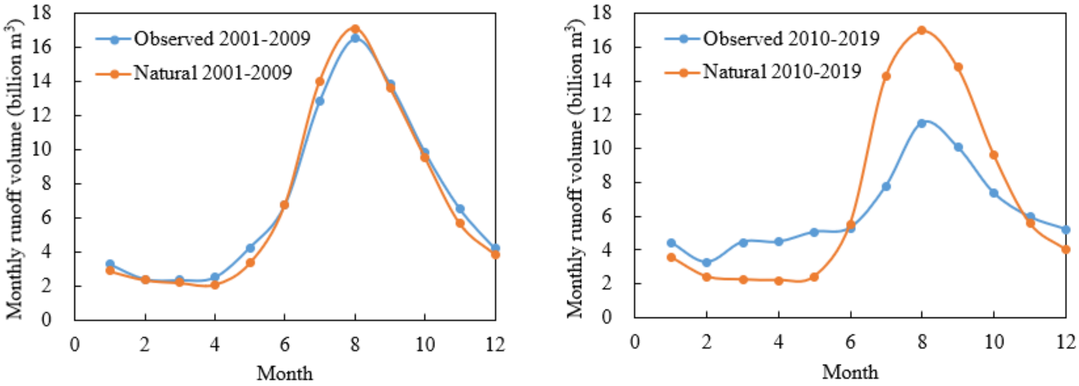

Figure 12. Natural and observed regime curves at Chiang Saen Hydrological Station

Chapter 4 Conclusions and Recommendations

4.1 Main findings

(1) Drought characteristics

The frequency of drought in the LMRB is high, and the average frequency of severe meteorological drought (SPEI<-1.5) is 7%. The highest frequency of severe meteorological drought in the basin occurs in the middle and upper areas of Lancang sub-region, reaching more than 12%. The severe and exceptional droughts occurred more frequently during the recent 59 years compared to its previous 60 years

The proportion of drought occurring in the dry season is significantly higher than that in the wet season, which implies that the normal operation mode of reservoirs, i.e., store water in flood season and release water in dry season, is conducive to drought relief in the LMRB as a whole.

For the year of 2019, the LMRB experienced one of the most severe droughts in the past century. The hot spot of the 2019 drought was located in the region from lower Lancang to upper Mekong (Nong Khai). The 2019 drought is characterized by a long duration and severely less precipitation since the early wet season.

(2) Natural runoff composition

Lancang River contributes significantly to annual discharge at Chiang Saen at the ratio of 64.4%. When it goes to the downstream of the Mekong River, the contribution ratio decreases substantially, with the ratio of 39.5% at Nong Khai, 24.9% at Nakhon Phanom, and 14.3% at Stung Treng. This means that the reservoirs located in the Lancang River may not supplement enough water when drought occurs in the downstream part of the Mekong River. Joint operation of all the reservoirs located in both mainstream and tributaries can be more supportive for the downstream drought.

(3) Impacts of reservoir regulation on the mainstream discharge

The Lancang cascade reservoirs store flood water in the rainy season and discharge more water in the dry season, which effectively increases the dry season streamflow of the Mekong River. Considering that the agricultural water demand peak of the Mekong sub-region happens in the dry season (Do et al., 2020), and the share of drought in the dry season is quite higher than that in the wet season, the water supplementary role of Lancang reservoir cascade can generally alleviate drought occurring in the Mekong River Basin.

4.2 Recommendations

(1) Integrated structural and non-structural measures to alleviate drought

The drought occurs more frequently in the dry season than the wet season in the LMRB. As the peak of agricultural water demand of Mekong Basin occurs in the dry season and water shortage is more likely to reduce agricultural production during this period, it is recommended that holistic measures are to be taken in dealing with the drought in the dry season, which include structural measures as well as non-structural measures such as strengthening the construction of water storage project and supporting canal system to improve the water supply capacity; adjusting the agricultural planting structure and selecting drought-resistant crop types; promoting the drought monitoring and early warning system; developing water-saving and drought-resistant irrigation and cultivation technology, etc.

(2) Joint operation of mainstream and tributary reservoirs for flood prevention and drought relief

According to the runoff composition analysis, the contribution ratio of Lancang River to mainstream discharge decreases to 39.5% at Nong Khai, and further decreases to 14.3% at Stung Treng. It should be noted that the overall storage capacity of reservoirs in the tributaries of Mekong River reaches more than 37.2 billion m^3 according to the data set from CGIAR research program on Water, Land and Ecosystems, and the value will over 100 billion m^3 until 2030 (Wang et al., 2017), which could play an important role of runoff regulation on the mainstream discharge of Mekong River. The drought in the LMRB is characterized by significant spatiotemporal asynchrony. It's recommended that riparian countries strengthen relevant research on joint operation of reservoirs in the upstream and downstream as well as in the mainstream and tributaries, so as to make good use of these reservoirs and provide technical support for the benefits of the whole basin.

(3) Joint research on a whole-basin flood and drought forecasting system

Strengthened cooperation is needed to cope with challenges as well as share benefits from and beyond the river. It is suggested that the experts from riparian countries carry out joint research to lay a solid foundation for reciprocal cooperation mechanisms. A whole-basin flood and drought forecasting system will aid in the endeavours of flood prevention and drought relief, and joint research efforts are deserved to be implemented.

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