FINAL REPORT

JOINT RESEARCH

HYDROLOGICAL IMPACTS OF THE LANCANG HYDROPOWER CASCADE ON DOWNSTREAM EXTREME EVENTS

Mekong River Commission,
Lancang-Mekong Water Resources Cooperation Center
China Institute of Water Resources and Hydropower Research
International Water Management Institute

October 2019

This document has been prepared by the following authors:

Dr. Janejira Chuthong
Chief Hydrologist
Mekong River Commission Secretariat (MRCS)

Dr. Hui Liu
Senior engineer
China Institute of Water Resources and Hydropower Research (IWHR)

Dr. Fengran Xu
Professor of engineering
China Institute of Water Resources and Hydropower Research (IWHR)

Dr. Dongsheng Cheng
Professor of engineering
Lancang-Mekong Water Resources Cooperation Center (LMWRCC)

Dr. Wenhai Zhang
Engineer
Lancang-Mekong Water Resources Cooperation Center (LMWRCC)

Dr. Mansoor Leh
Researcher – Water Accounting
International Water Management Institute (IWMI)

Dr. Guillaume Lacombe
Senior Researcher – Water Resources and Hydrology
International Water Management Institute (IWMI)

With contributions from the teams as listed in Annex 1

Document History

Version	Revision	Description	Issue date	Issued by
1	0	Draft Report	April 2019	Janejira Chuthong – MRCS Hui LIU and Fengran Xu -IWHR Guilaume and Mansoor – IWMI
2	0	Final Draft Report	August 2019	Janejira Chuthong – MRCS Anoulak Kittikhoun - MRCS Hui LIU and Fengran Xu -IWHR Mansoor – IWMI
3	0	Final Report (un-edited)	October 2019	Janejira Chuthong – MRCS Anoulak Kittikhoun - MRCS

Table of Contents

List of Figures

List of Tables

Executive Summary

The Lancang-Mekong Basin is exposed to natural disasters such as floods and droughts. The Mekong region experienced more than 300 floods and storm surges between 1970 and 2012[1]. In the Yunnan Province of China, the frequency of droughts has increased recently, with the years 2009-2011 experiencing continuous drought at an unprecedented level. Frequent floods and droughts pose major threats to the livelihoods, properties and lives of the people in the riparian countries.

To assess the role of the Lancang cascade reservoirs on downstream floods and droughts and to explore the potential for mutual benefit upstream-downstream collaborations, the six riparian countries agreed, during the 20th MRC Dialogue Meeting (with China and Myanmar), to conduct a joint assessment to examine the links between floods and droughts with the Lancang cascade reservoirs. This research activity is a joint effort between the Mekong River Commission Secretariat (MRCS), the China Institute of Water Resources and Hydropower Research (IWHR) of the Ministry of Water Resources (MWR) of China, the International Water Management Institute (IWMI), the Lancang-Mekong Water Resources Cooperation Center (LMWRCC), and the National Mekong Committees.

The research comprised the following 3 scopes with responsible research teams:

1) Comparative study of the droughts of 2009-2010 and 2012-2013

IWHR and LMWRCC performed an analysis of the Standardized Precipitation Index (SPI) drought indicator based on the GLDAS rainfall data and evaluated flow contribution at Jinghong to downstream stations for the dry seasons of 2009-2010 and 2012-2013.

2) Analysis of the drought of 2015-2016

MRC Secretariat evaluated the effect of the emergency water supplement from China for the drought of 2015-2016 by analyzing daily water level, discharge, and long-term average of dry season flow conditions of 1960-2009 and 2010-2015. The evaluation focused on influential hydrological factors of Mekong water flow and volume.

3) Analysis of the respective hydrological impacts of climate variability and hydropower operation

IWMI developed a conceptual rainfall-runoff model covering the whole Lancang-Mekong Basin to simulate occurrence, magnitude of hydrological changes with a cross simulation matrix over the dry season of 2009-2010, 2012-2013, 2015-2016, including the flash flood of December 2013.

The following sections summarized the methodology and key findings from the studies in three major topics above.

Comparative analysis of the droughts of 2009-2010 and 2012-2013

The Lancang-Mekong Basin experienced a severe drought from October 2012 to April 2013, with an estimated return period of 50-year to 100-year. The drought caused extensive damages to water supply, agricultural production and livelihood of people. A preliminary analysis of the weather patterns performed by China Institute of Water Resources and Hydropower Research suggests that this drought was similar in terms of spatial distribution and magnitude to the drought that occurred

[1] Mekong River Commission (2015). Annual Mekong Flood Report 2013, Mekong River Commission, Vientiane, 102 pages.

between October 2009 and April 2010. The main hydrological difference between these two droughts is likely caused by the Xiaowan Dam that was not completed and could not store water during 2009-2010, but was operational by September 2012 and already achieved its operational water storage target, releasing an additional 7.2 km^3 of water from November 2012 to April 2013. The enhanced dry season minimum flow resulted in a water level 0.5 m higher than that observed during the dry season of 2009 at Chiang Saen and Luang Prabang stations.

This comparative study compared the two drought events from the meteorological and hydrological perspective, and analyzes the impact of water supplement from Lancang hydropower cascade on the hydrological process of the Mekong River during the dry seasons of 2009-2010 and 2012-2013. The analysis was based on SPI, SRI and hydrological frequency analysis, aimed to better understand the respective influences of the climate and the operation of the Lancang cascade reservoirs on downstream low flows. Experience on successful dam operations at times of drought was also synthesized for improved collaborations between China and downstream riparian countries in the future. Findings from the analysis are as followings:

- The inter-annual variation of meteorological drought is not significant. The results from SPI analysis show that the rainfall in Chiang Saen subbasin is characterized by alternation of high and low period, and there is no obvious trend. The rainfall in Mukdahan subbasin and Stung Treng subbasin has a slightly downward trend.
- The dry season drought in 2009-2010 and 2012-2013 was comparable in the upper reaches of the Lancang-Mekong River Basin. The drought in the lower reaches of the Lancang-Mekong River Basin in 2012-2013 was more severe than that of 2009-2010. The drought in 2009-2010 mainly occurred from December to February, and that of 2012-2013 mainly occurred from November to January. The two droughts reached moderate or severe level. The SPI6 results in the Stung Treng subbasin show that the dry season of 2012-2013 mostly belongs to moderate drought, and that of 2009-2010 mostly belongs to light drought.
- The inter-annual variation of dry season runoff along the Mekong mainstream shows a significant upward trend. The results of SRI6 from 1985 to 2016 show that the discharge of hydrological stations (Chiang Saen, Mukdahan and Stung Treng) along Mekong mainstream shows a significant upward trend. The most severe period of hydrological drought in the upper reaches of the Mekong River was in the late 1990s, and that of the middle and lower reaches was in the late 1980s and early 1990s.
- In the dry season of 2012-2013, no hydrological drought occurred along the Mekong mainstream. The discharge along Mekong mainstream was slightly or significantly greater than the multi-year average, and there was no hydrological drought occurred. The analysis of hydrological frequency in the dry season shows that the drought recurrence period of the minimum daily and monthly discharge of Chiang Saen Station in 2009-2010 is more than 12 years, while the discharge of 2012-2013 dry season has reached the multi-year average.
- The Lancang hydropower cascade has a positive impact on the discharge and water level of the Mekong mainstream in the dry season. Due to the regulation of Lancang hydropower cascade, the monthly discharge and water level of Chiang Saen station in dry season of 2012-2013 were higher than the multi-year averages. The monthly discharge and water level of other hydrological stations along the Mekong mainstream after January 2013 were higher than the multi-year averages. The rise of water level could also be partly due to rainfall in downstream sections of Lancang River.
- The water supplement of Lancang hydropower cascade had increased the water volume of the Mekong mainstream in the dry season. In the dry season of 2012-2013, the water volume

at Jinghong station was 5.08 billion m^3 more than the multi-year average, and 6.70 billion m^3 more than that of 2009-2010. For the dry season water volume at Chiang Saen station in 2012-2013, it was increased from multi-year average 17.79 billion m^3 to 23.15 billion m^3, with an increase of 5.36 billion m^3, and it was also 5.89 billion m^3 more than that of 2009-2010.

Analysis of extreme drought of 2015-2016

The meteorological and agricultural drought conditions in 2015-2016 over the Mekong Basin had triggered China to implement its emergency water supplement from its cascades dams in the Lancang River to the Mekong River to help mitigate impact of the drought on downstream countries by increasing the water discharge from Yunnan's Jinghong Reservoir. China implemented its **emergency water supplement in a 'three-phase plan'**: (1) from **9 March to 10 April 2016**, with an average daily discharge of no less than 2,000 m^3/s; (2) from **11 April to 20 April 2016** with the discharge of no less than 1,200 m^3/s; and (3) from **21 April to 31 May 2016** with the discharge of no less than 1,500 m^3/s. The Mekong River Commission acknowledged this action by China, in which China stated that it implemented the water supplement at a challenging time, especially within the context where China itself was also suffering from drought, which had affected its household water supply and agricultural production.

The China's Ministry of Water Resources and Mekong River Commission Secretariat then co-organised experts from both sides to conduct a Joint Observation and Evaluation (JOE) of the Emergency Water Supplement from China and its effect of easing the drought situation in the Mekong Basin.

The scope of the Joint Observation and Evaluation covered: (1) Temporal Scope – dry season of 2016, which runs from 1 December 2015 to 31 May 2016 and especially during the emergency water supplement period from 15 March to 15 May 2016; and (2) Spatial Scope – from Jinghong hydrological station on the Lancang River to the Mekong Delta.

It is found that the **emergency water supplement from China increased water level** and **discharge** along the Mekong mainstream and **contributed in decreasing salinity intrusion** in the Mekong Delta. The findings reveal evidence that explain the positive hydrological impacts of the Lancang cascade reservoirs on the downstream droughts as summarized below.

- **Reduced rainfall amount and inflow discharge** to the Lancang Basin have been observed in the dry season of 2016. Likewise, the Mekong Basin has experienced abnormally dry conditions with **high temperature** and **less rainfall**. These meteorological and agricultural droughts are strongly believed to be impacted by the **super El Niño 2015-2016**. Monitoring of flow conditions on the mainstream suggests that water level and discharge in the dry season of 2016 at Vientiane/Nong Khai and Stung Treng in December 2015 were few days below the long term minimum of 1960-2009. However, thanks to the emergency water supplement from China, the **water level** and **discharge** at most stations along the Mekong mainstream were most of the time **above the long term average** and even higher than the long term maximum in March and April 2016.
- Total volume released at Jinghong was **12.65 billion m^3**: 6.10 billion m^3 from 9 March to 10 April 2016, 1.07 billion m^3 from 11 April to 20 April 2016, and 5.48 billion m^3 from 21 April to 31 May 2016.
- During the period of the emergency water supplement in March and April 2016, the monthly discharges at Jinghong were 1,280 m^3/s and 985 m^3/s respectively, larger than the average of 1960-2009, and 704 m^3/s and 442 m^3/s respectively, higher than the average of 2010-2015.

- The emergency water supplement from China arrived at **Chiang Saen on 11 March** and increased till 14 March 2016. This pattern reached **Luang Prabang on 14 March**, **Chiang Khan on 17 March**, **Nong Khai on 19 March**, **Nakhon Phanom on 22 March**, **Mukdahan on 23 March**, **Pakse on 25 March**, **Stung Treng on 27 March**, **Kratie on 28 March** and **Tan Chau on 1 April 2016**. Similarly, the emergency water supplement **increased water level** or **discharge** along the Mekong mainstream to an overall extent of **0.18-1.53 m** or **602-1,010 m^3/s**. Equally, the maximum salinity in the Mekong Delta decreased by 15% and 74%, and the minimum salinity decreased by 9% and 78% according to observation stations.
- Monitoring at Chiang Khan suggests that additional water of 300 m^3/s for one day on top of the emergency water supplement from China was detected on 27 March 2016. This additional water arrived at Nong Khai on 28 March, at Nakhon Phanom on 31 March, at Mukdahan on 1 April, at Pakse on 3 April and at Stung Treng on 4 April 2016. Immediately after the peak of the additional water, a drop in discharge of 300 m^3/s was recorded on 31 March 2016.
- Total **volume in the dry season of 2016** (December 2015 to May 2016) at Jinghong presented huge portion (**40%-89%**) of the total volume at different stations along the Mekong mainstream. Additionally, the volume from 10 March to 10 April 2016, which was first period of the emergency water supplement, claimed significant portion, specifically 99% at Chiang Saen, 92% at Nong Khai and 58% at Stung Treng. Similarly, **net contribution of the water supplement** in term of discharge to total discharge was **47% at Jinghong**, **44% at Chiang Saen**, **38% at Nong Khai** and **22% at Stung Treng**. This contribution also alleviated salinity intrusion in the Mekong Delta.

Analysis of the respective hydrological impacts of climate variability and hydropower operation

This study aimed at seeking to differentiate the effects of actual hydropower dam operation and climate variability on streamflow for two sub-basins of the Lancang-Mekong basin, namely Chiang Saen and Luang Prabang. The observed and simulated discharge data were compared under different conditions and time periods i.e. before dam development (before 2009) and post dam development (after 2009). The GR4J model was applied to simulate streamflow at the two stations. The model was calibrated with observed gauge data for the period 1998-2008 when there was minimal hydropower dam operations in the basin. Then the calibrated model was used to simulate streamflows for the period 2009-2016 assuming no hydropower dam development. Simulated streamflow under "natural" conditions were then compared to observed streamflow for the period 2009-2016 after significant hydropower dam development happened within the basin.

Besides, the dry seasons of 2009/2010, 2012/2013 and 2015/2016 were evaluated to assess the magnitude and occurrence of hydrological changes within these periods. The following observations can be made from the study:

- Both the Chiang Saen and Luang Prabang stations have experienced significant hydrological change from 2009-2016 compared to 1998-2008.
- There has been increased streamflows during the dry seasons of 2012/2013 and 2015/2016 which can be attributed mainly to hydropower influences.
- The flash flood of December 2013 is attributed to rainfall in downstream sections of Lancang River, not the regulation of Lancang hydropower cascade.

1 Introduction

1.1 Background

The Lancang River originates from the northern slope of the Tanggula Mountains in the Yushu Tibetan Autonomous Prefecture of the Qinghai Province, China. The river flows south through the Dai Autonomous Prefecture of Xishuangbanna in Yunnan Province before leaving China. Also, known as the Mekong River in downstream countries, it passes Myanmar, Lao PDR, Thailand, Cambodia, and Viet Nam, before emptying into the Sea. In China, the river has a catchment area of 164,400 km^2 with an average discharge of 64 billion m^3 per annum, which account for 20.7% and 13.5%[2] of the area and discharge of total Lancang-Mekong system, respectively.

The Lancang-Mekong Basin is exposed to natural disasters such as floods and droughts. The Mekong region experienced more than 300 floods and storm surges between 1970 and 2012[3]. In the Yunnan Province of China, the frequency of droughts has increased recently, with the years 2009-2011 experiencing continuous drought at an unprecedented level. Frequent floods and droughts pose major threats to the livelihoods and lives of the people in the riparian countries.

The Lancang-Mekong Cooperation Mechanism was officially inaugurated during the first Lancang-Mekong Cooperation (LMC) Leaders' Meeting held in Sanya, China on 23 March 2016. It marks a closer collaboration for ‘shared river, shared future’. Among the five priority areas agreed, water cooperation is identified as a flagship area in the LMC.

The Lancang-Mekong River is a transboundary river flowing through six countries, therefore water resources development and conservation of this important river is a concern shared by the riparian countries. Six hydropower reservoirs have been commissioned on the mainstream of the middle and lower reach of the Lancang River, namely Gongguoqiao, Xiaowan, Manwan, Dachaoshan, Nuozhadu and Jinghong. Of these dams, the Xiaowan and Nuozhadu reservoirs have multi-year regulation capacity, totalling 21.2 km^3. In the Mekong River Basin, existing hydropower reservoirs have been mainly built on the tributaries. While 11 dams have been proposed, and are in various stages of planning on the mainstream, Xayaburi is the first one on the Mekong River where construction commenced in Lao PDR in 2012.

Hydropower development can provide important contributions to poverty reduction and sustainable development in the region. It provides much needed energy for rapid economic growth, and reduces reliance on non-renewable energy. Large dams such as Xiaowan and Nuozhadu have potential role to store flood water and increase low flows. Coordinated and optimised operation of the large dams could make substantial positive contributions to improved flood control, drought mitigation, hydropower generation, irrigation opportunity and navigation.

The impacts of hydropower are also a subject of debate in the international development agenda. One controversial question is about the role and contribution of the hydropower dams built along the Lancang River in China to recent flood and drought events experienced by downstream countries.

[2] In documents of the Mekong River Commission, the contribution from China to the annual discharge is 17%.

[3] Mekong River Commission (2015). Annual Mekong Flood Report 2013, Mekong River Commission, Vientiane, 102 pages.

However, there is limited knowledge about the relative contributions of climate conditions, hydrological changes, and the role of reservoirs in the creation of these harmful episodes.

To assess the role of the Lancang cascade reservoirs on downstream floods and droughts and to explore the potential for win-win upstream-downstream collaborations, the six riparian countries agreed, during the 20th MRC Dialogue Meeting (with China and Myanmar) in July 2016, to conduct a joint assessment to examine the links between floods and droughts with the Lancang cascade reservoirs. Also, it fits well in the framework of the proposed Lancang-Mekong Water Resources Center.

The research activity is a joint effort between the China Institute of Water Resources and Hydropower Research (IWHR), International Water Management Institute (IWMI), Lancang-Mekong Water Resources Cooperation Center (LMWRCC), Mekong River Commission Secretariat (MRCS), and National Mekong Committees.

China (by IWHR team) invited the Member Countries, MRCS, IWMI and other relevant parties to a joint visit to Jinghong and Nuozhadu hydropower and corresponding river section, on 22-26 September 2016, to gain first-hand knowledge of the study area in the Lancang section. After the joint visit, the draft proposal was revised by the MRCS, IWMI and China, considering a wider and clearer scope of the research, identification of data and information needed and finetuning research methodology. The draft proposal was submitted to the Member Countries for their review in April 2017 and their comments and suggestions were provided back in June/July 2017.

During the 21st Dialogue Meeting on 24 August 2017 in Vientiane, the Mekong River Commission Secretariat (MRCS) was advised and suggested by the Member Countries to organize a Regional Consultation Meeting on Finalization of the Proposal of the Joint Research. Finally, the Proposal of the Joint Research has been approved and implemented according to agreed work plan indicated in the proposal after the Regional Consultation in Siem Reap on 3 October 2017. As part of the Joint Research and agreed during the meeting in Siem Reap, a field visit to the Mekong river in Nakhon Phanom Province was organized by MRCS on 13-14 December 2017.

1.2 Objectives

The Joint Research on Hydrological Impacts of the Lancang Hydropower Cascade on Downstream Extreme Events is part of the cooperation between the Mekong River Commission and Lancang-Mekong Cooperation Mechanism and exploration of effective collaboration between the China Institute of Water Resources and Hydropower Research (IWHR), International Water Management Institute (IWMI), Lancang-Mekong Water Resources Cooperation Center (LMWRCC), and Mekong River Commission Secretariat (MRCS), and Lancang-Mekong countries (including Myanmar).

The project is expected to: (1) build trust, foster technical cooperation, and help clarify the impact of Lancang-Mekong hydropower development for the riparian countries and international development community; (2) contribute to improved cooperation between riparian countries for flood protection and drought mitigation; and (3) help establish models of successful cooperation, and facilitate greater collaboration for peace and development in the Lancang-Mekong region.

1.3 The scope of the Joint Research

Hydropower dams alter seasonal flow of rivers. In tropical monsoonal climate of Southeast Asia, hydropower reservoirs usually accumulate large volumes of water during the flood season and release it during the dry season. Impacts include the attenuation of flood peaks during the wet season and the enhancement of dry season flow. However, these effects are partly compounded by the inter-annual climate variability, making a hydrological impact assessment somewhat complex. For this reason, the proposed study would apply a simple rainfall-runoff model to isolate the hydrological effect of the inter-annual variability of rainfall from the effects of other environmental changes, such as operations of hydropower systems.

Recent hydrological monitoring reveals that flows from the Lancang River have a notable hydrological influence on the Mekong River, gradually decreasing in influence down to the Mekong Delta. This study hence focuses on the mainstream section of the Lancang-Mekong River, from Jinghong in China, to Kratie in Cambodia. The hydrological assessment considers several dry seasons (October to May) of specific years characterized by extreme events. The following describes 3 specific scopes of the research.

1.3.1 Comparative analysis of the droughts of 2009-2010 and 2012-2013

The Lancang-Mekong Basin experienced a severe drought from October 2012 to April 2013, with an estimated return period of 50-year to 100-year. The drought caused extensive damages to water supply, agricultural production and livelihood of people. A preliminary analysis of the weather patterns performed by China Institute of Water Resources and Hydropower Research (IWHR) of the Ministry of Water Resources (MWR) of China – IWHR/MWR suggests that this drought was similar in terms of spatial distribution and magnitude to the drought that occurred between October 2009 and April 2010. The main hydrological difference between these two droughts is likely caused by the Xiaowan Dam that was not completed and could not store water during 2009-2010, but was operational by September 2012 and already achieved its operational water storage target, releasing an additional 7.2 km^3 of water from November 2012 to April 2013. The enhanced dry season minimum flow resulted in a water level 0.5 m higher than that observed during the dry season of 2009 at Chiang Saen and Luang Prabang stations.

The comparative analysis of the droughts of 2009-2010 and 2012-2013 aims to better understand the respective influences of the climate and the operation of the Lancang cascade reservoirs on downstream low flows. Experience on successful dam operations at times of drought was also be synthesized for improved collaborations between China and downstream riparian countries in the future.

1.3.2 Analysis of extreme drought of 2015-2016

The drought of 2015-2016 in the Lancang-Mekong river basin is the most serious of the past decades. As the drought situation worsened, a ‘three phases’ emergency water supplement was carried out by the Ministry of Water Resources of China to supply water from the Lancang River to the Mekong River to help mitigate impact of the drought on downstream countries. A Joint Observation and Evaluation (JOE) has been conducted and a Technical Report was jointly prepared by the MRC and MWR evaluating the effects of the emergency water supplement. The findings reveal evidence that explain the positive hydrological impacts of the Lancang cascade reservoirs on the downstream droughts.

1.3.3 Analysis of the flash flood of December 2013

Between the 13 and 15 December 2013, a significant intense rainfall event has been recorded downstream of the Jinghong reservoir (248.5 mm at Guanlei station). This series of major rainfall events resulted in a series of unusually high flows. There were suspicions that the flash flood was caused by releases from the Lancang cascade reservoirs[4]. A hydrological assessment of such extreme events would help improve the understanding of the regional floods and help better prepare in downstream countries to reduce damages.

[4] Financial Times: China silent on damaging Mekong floods, Pilita Clark. Accessed on 18 July 2014, http://video.ft.com/3682662151001/China-silent-on-damaging-Mekong-floods/World.

2 Data and methodology

The Joint Research were conducted by an international research team including (1) IWHR, (2) IWMI, (3) LMWRCC, (4) MRCS and (5) National Mekong Committees. The study includes the collection of hydro-meteorological data that were recorded during the 4 extreme events. The data includes (a) observations from meteorological stations located in the Lancang-Mekong River Basin, (b) continuous multi-year daily flow time series from the main gauging stations along the Mekong mainstream, (c) monthly/daily flow time series from Jinghong and Guanlei stations on Lancang River during the droughts and the flash flood of 2013, respectively, and (d) daily areal rainfall and standard evapotranspiration time series derived from gridded products over the catchment of the Lancang-Mekong Basin. The data was used for analysis using statistical tools and conceptual hydrological modelling. Researchers conducted field and exchange visits to better understand the study area and objectives, and to discuss on-going analyses and results. The hydrological coupling effects of the Lancang cascade reservoirs with downstream extreme events were established for the Lancang-Mekong River.

2.1 Data collection

The following section describes data type and data collection responsibility. All data collected by the project partners were exchanged and shared.

Data collected by IWHR and LMWRCC:

1. Monthly rainfall over the Lancang-Mekong Basin from the Global Land Data Assimilation System (GLDAS), covers the interest period from October 2009 to May 2010 and from October 2012 to May 2013;
2. Monthly water level and discharge at Jinghong from October 2009 to May 2010 and from October 2012 to May 2013;
3. Daily water level and discharge at Jinghong and daily water level at Guanlei stations from December 2013 to January 2014; and
4. Daily rainfall data at typical meteorological stations in the Lancang Basin in December 2013.

Data collected by IWMI:

1. Daily rainfall and standard evapotranspiration time series from gridded products (e.g. CHIRPS - Climate Hazards Group InfraRed Precipitation with Station data[5] and USGS FEWS Global daily PET product)[6] over the Lancang-Mekong Basin from 1981 to near-present.

Data collected by MRCS:

[5] http://chg.geog.ucsb.edu/data/chirps/

[6] https://earlywarning.usgs.gov/fews/product/81#documentation

1. Daily water level and discharge data at mainstream hydrological stations upstream Kratie from 1985 to near-present[7]; and
2. Daily rainfall data at the typical meteorological stations in the Mekong Basin from December 2013 to January 2014.

The data collected by the IWMI and MRC, listed here-above, were used as input to run the rainfall-runoff model detailed in the methodology section 4.2: "Analysis of the respective hydrological impacts of climate variability and hydropower operation".

2.2 Methodology

The research activity is a joint effort between the China Institute of Water Resources and Hydropower Research (IWHR), International Water Management Institute (IWMI), Lancang-Mekong Water Resources Cooperation Center (LMWRCC), Mekong River Commission Secretariat (MRCS), and National Mekong Committees. Each party was to conduct the following studies/analysis with agreed methodologies.

1) Comparative study of the droughts of 2009-2010 and 2012-2013

IWHR and LMWRCC performed an analysis of the Standardized Precipitation Index (SPI) drought indicator based on the GLDAS rainfall data and evaluated flow contribution at Jinghong to downstream stations for the dry seasons of 2009-2010 and 2012-2013.

2) Analysis of the drought of 2015-2016

MRC evaluated the effect of the emergency water supplement from China for the drought of 2015-2016 by analyzing daily water level, discharge, and long-term average of dry season flow conditions of 1960-2009 and 2010-2015. The evaluation focused on influential hydrological factors of Mekong water flow and volume.

3) Analysis of the respective hydrological impacts of climate variability and hydropower operation

IWMI developed a conceptual rainfall-runoff model covering the whole Lancang-Mekong Basin to simulate occurrence, magnitude of hydrological changes with a cross simulation matrix over the dry season of 2009-2010, 2012-2013, 2015-2016, including the flash flood of December 2013.

Further detailed methodology and responsibility of parties involved are presented below.

IWHR and LMWRCC	IWMI	MRCS
(1) Comparative analysis of the droughts of 2009-2010 and 2012-2013 The Standardized Precipitation Index (SPI) drought indicator was calculated based on the GLDAS rainfall data. The flow contribution at Jinghong to downstream stations during the two selected drought events were calculated. The flow were compared between the dry seasons of 2009-2010 and 2012-2013 at Mekong mainstream stations.		
IWHR and LMWRCC took a lead in this activity by collecting and providing relevant data/information,	IWMI contributed in reviewing the data analysis and results, and jointly writing the section report.	MRCS assisted in checking input data of GLDAS, providing hydrological data on the mainstream and jointly

[7] Note that, although this joint study is focusing on the dry seasons, it requires continuous daily flow time series including wet and dry seasons, to calibrate the model and to detect the respective effects of climate variability and hydropower operation on river flow.

<table>
<tr><th>IWHR and LMWRCC</th><th>IWMI</th><th>MRCS</th></tr>
<tr><td>performing analysis of the SPI and evaluation of flow contribution at Jinghong and comparison, and jointly preparing the section report.</td><td></td><td>performing analysis and flow contribution and comparison, contributing to jointly write the section report.</td></tr>
<tr><td colspan="3">(2) Analysis of the drought of 2015-2016
The effect of the emergency water supplement from China for the drought of 2015-2016 was evaluated by analyzing daily water level, discharge, and long-term average of dry season flow conditions of 1960-2009 and 2010-2015. The evaluation focused on the generic analyses of the drought in the Lancang-Mekong Basin and influential hydrological factors of Mekong water flow/volume of the emergency water supplement. The findings from this study were primarily used for this section.</td></tr>
<tr><td>IWHR and LMWRCC contributed in reviewing the data analysis and results, and jointly writing the section report.</td><td>IWMI contributed in reviewing the data analysis and results, and jointly writing the section report.</td><td>MRCS took a lead in this activity by extracting findings from the Joint Observation and Evaluation of the Emergency Water Supplement from China to the Mekong River and jointly write the section report.</td></tr>
<tr><td colspan="3">(3) Analysis of the respective hydrological impacts of climate variability and hydropower operation.
This analysis considered the whole Lancang-Mekong Basin over all studied dry seasons: 2009-2010, 2012-2013, 2015-2016, including the flash flood of 2013.</td></tr>
<tr><td>IWHR and LMWRCC contributed in reviewing the data analysis and results, and jointly writing the section report.</td><td>IWMI did lead this activity: a conceptual rainfall-runoff model (daily GR4J or monthly GR2M) would be calibrated over successive 1-year periods and the calibrated models would be re-run with rainfall input from other years of the study period, thus yielding a cross simulation matrix. This matrix would be used to differentiate the effects of actual hydropower operation and climate on downstream flow. It should be noted that this model cannot simulate hydropower operation. The occurrence and magnitude of possible hydrological changes would be compared to the years and capacity of the new hydropower dams to assess their role in the events. Correlations between times series of flows recorded along the Mekong Mainstream would be analysed to characterize downstream flow propagation of dam releases.

In parallel to this modelling framework based on cross-simulation matrices, the conceptual model would be recalibrated over the periods 1985-2008 and 2009-2016 to enable a consistency check with the DSF modelling performed by the MRC.</td><td>MRCS provided hydrological data on the mainstream and perform analysis using calibrated and validated MRC Decision Support Framework (DSF) of 1985-2008. The results for 1985-2008 from IWMI and MRC would be evaluated. Additionally, for flash flood event in 2013, MRC would conduct analysis on the event using the products of Satellite and ground observation rainfalls and flow propagation along the Lancang-Mekong mainstream. The section report would be jointly prepared.</td></tr>
</table>

2.3 Working mechanism and proposed work plan

Proposed time frame	Activity	Responsibility
September 2016 (+4 months)	Conducting technical field trip to the Lancang River section Discussing initial draft proposal	IWHR to facilitate and prepare for the technical field trip and IWMI, MRCS and National Mekong Committees to participate and contribute to discussion on the draft proposal
January 2017 (+2 months)	Drafting proposal with inputs from all concerned parties	IWHR, IWMI and MRCS to prepare first draft proposal
March 2017 (+1 month)	Preparing second draft proposal	IWHR, IWMI and MRCS to revise the first draft proposal
April 2017 (+3 months)	Finalising draft proposal and sending to the National Mekong Committees	IWHR, IWMI and MRCS to finalise the draft proposal MRCS to send to National Mekong Committees
July 2017 (+3 months)	Addressing comments and suggestion from the National Mekong Committees	IWHR, IWMI and MRCS to finalise the draft proposal. MRCS to discuss with National Mekong Committees
October 2017 (+1 month)	Regional consultation meeting with the National Mekong Committees	MRCS to ordinate and work with National Mekong Committees
November 2017 (+1 month)	Refining research methodology considering available data and resources	IWHR, IWMI, LMWRCC, MRCS and National Mekong Committees together to refine the final proposal
December 2017 (+3 months)	Collecting required data and information	China, IWMI and MRCS to collect required data and make it available to all relevant parties
December 2017 (+3 months)	Conducting technical field trip to the Mekong River	MRCS and National Mekong Committees to facilitate and prepare for the technical field trip and IWHR, IWMI, LMWRCC, National Mekong Committees to participate
March 2018 (+2 months)	Exchanging relevant collected data Conducting analyses	IWHR, IWMI, LMWRCC, MRCS and National Mekong Committees together to conduct analyses
May 2018 (+2 months)	Writing draft technical report	IWHR, IWMI, LMWRCC and MRCS to contribute their responsible section reports and MRCS to put them together and compile draft technical report
July 2018 (+3 month)	Reviewing results of analyses and draft technical report Conducting final workshop (in Vientiane – to be confirmed)	National Mekong Committees to review and provide comments and suggestion to draft technical report All parties to facilitate the workshop (in Vientiane – to be confirmed), and MRCS, IWHR, LMWRCC and National Mekong Committees to participate
October 2018 (+1 month)	Finalising draft technical report	IWHR, IWMI, LMWRCC and MRCS to finalise draft technical report
November 2018 (+1 month)	Disseminating technical report	IWHR, IWMI, LMWRCC, MRCS and National Mekong Committees to disseminate the technical report

2.4 Expected outputs

A Technical Report jointly developed by the international research team on comparative analysis of the droughts and downstream hydrological effects of the dams of 2009-2010 and 2012-2013; the evaluation of effect of water supplement during the drought of 2015-2016; the analysis of the high flows in December 2013 and the contributing factors.

The findings from the Technical Report would be widely disseminated by the team and presented in the future Joint MRC and LMC Regional Workshop with participation from all relevant stakeholders to be decided and invited by the MRC, IWMI, IWHR and LMWRCC.

2.5 Role and responsibility

IWHR

- To prepare and arrange field and exchange visit to the Lancang River section and coordinate with IWMI, MRC and National Mekong Committees
- To facilitate, support and provide hydrological data/information
- To conduct and contribute to analyses in the study
- To contribute to writing of the Technical Report of the Joint Research

IWMI

- To organize a workshop at IWMI Southeast Asia Regional Office in Vientiane (to be confirmed), to present the preliminary results of the study and discuss next steps,
- To facilitate, support and collect hydrological data/information with a focus on gridded rainfall and potential evapotranspiration over the catchment of the Lancang-Mekong Basin
- To perform the hydrological modelling and analysis based on cross-simulation matrices
- To contribute to writing of the Technical Report of the Joint Research

LMWRCC

- To provide technical support on methodology, analysis, and results of the study
- To provide communication support
- To contribute to writing of the Technical Report of the Joint Research

MRCS

- To prepare and arrange field and exchange visit to the Mekong River section, and coordinate with the National Mekong Committees, China and IWMI
- To facilitate, support and provide hydrological data/information
- To conduct and contribute to analyses in the study
- To contribute to writing of the Technical Report of the Joint Research

National Mekong Committees

- To collaborate by joining field and exchange visit to the Lancang and Mekong Rivers sections

- To facilitate, support and provide additional data and information if required
- To provide comment on collected data, methodology, analysis and results of the study
- To review the Technical Report

Myanmar

- To facilitate, support and provide additional data and information if required
- To review and comment the Technical Report if needed

3 Field and exchange visits

3.1 Joint Visit to Lancang River, China, 22-26 September 2016

After the 20th Dialogue Meeting in July 2016, China (by IWHR team) invited the MCs, MRCS, IWMI and other relevant parties to a joint visit to Xiaowan, Jinghong and Nuozhadu reservoir and corresponding river section in Yunnan Province, China, on 22-26 September 2016, to gain first-hand knowledge of the study area in the Lancang section.

Twenty-four participants of the joint visit consisted 2 staff from MRC Secretariat, 8 representatives from National Mekong Committee Secretariats of 4 Member Countries, 1 international consultant, 1 representative from IWMI, 3 representatives from IWHR, and other 5 officers from China.

The participants visited the Xiaowan, Nuozhadu and Jinghong reservoirs, and the corresponding river sections. A meeting was organized during this visit in Dali to discuss the research scope and work plan. This activity made the experts better understand the study area, enhanced mutual understanding and promoted the progress of the joint research.

Group photo on the Nuozhadu dam

Communication with local experts from Hydro Lancang

Introduction of Lancang hydropower cascade

Visit the fish multiplication station

Downstream river section of Nuozhadu Reservoir

Travel from Nuozhadu Reservoir to Jinghong Hydropower Station

Figure 3.1-1 | Photos during the visit to the Nuozhadu Reservoir.

Inside the powerhouse of Jinghong Hydropower Station

Group photo on the dam of Jinghong Hydropower Station

Figure 3.1-2 | Photos during the visit to the Jinghong Hydropower Station.

Group photo in front of the Xiaowan Reservoir

Technical communication on the dam of the Xiaowan Reservoir

Figure 3.1-3 | Photos during the visit to the Xiaowan Reservoir.

Figure 3.1-4 | Meeting during the Joint Visit on 25 April 2017.

A meeting was held during this joint visit, the research scope and arrangement of the joint research was deeply discussed. The record of the meeting was concluded in the next paragraphs, which played an important role to promote this cooperation.

IWMI evaluated this field visit as a very interesting and valuable exchange to see the dams and meet with the project partners from China and the Lower Mekong countries. The following concerns were expressed, 1) As to the influential factors of the drought comparison, the main change is the dam, but there are also other factors, like monsoon of previous year which could complicate the hydrological change attribution to the hydropower dams; 2) Daily time step is more suited than monthly time step for the analysis of the flash-flood in December 2013. For this reason, it would be useful to work with daily water level, flow and rainfall; 3) The period before the flash flood should be included, for example start from the beginning of December 2016; 4) The work schedule of finish this Joint Research in August is ok for IWMI side, as long as data are available on time.

MRCS stated that 1) although the proposal has been discussed and agreed during the Twentieth Dialogue Meeting, this is the first time that the details be presented to the Member Countries. 2) There are different types of drought, the Lancang-Mekong countries experienced meteorological drought due to high temperature and little rainfall, when we talked about the river, it is more related to hydrological drought. 3) MRCS also asked about the scale of rainfall data sharing, suggested the spatial scale of flash flood study extend to Stung Treng, and the temporal scale extended to the previous wet season of the droughts. 4) The proposed work plan maybe a little tight for MRCS, since inner procedures may cost long time.

VNMC thought this is a great opportunity to visit the hydropower cascade in person and appreciated the arrangement. More data sharing and joint study should be carried out in the future.

CNMC 1) thanked the invitation from MWR of China, the support and coordination of Hydrolancang, Changjiang Water Commission and IWHR. It is great to see the dams in person other than hear about them from newspapers, through this visit we know the local people, landscapes, and the operation of dams which is introduced by directors of the dams. 2) The reform and new recruitment is undertaken in the MRCS, but not at the joint committee level. Inner procedures are always required in MRC, it would take time, but we would do our best to meet the time schedule of finalizing the proposal by the end of this year. 3) Besides the inner procedures, there are other factors like data availability. We could work at two steps, first is the senior experts working together, second is management level providing comments.

TNMC appreciated the invitation of MWR to carry out this interesting field trip. In general we support the proposal. For the work plan, we suggest more exchange visits and workshop during the research.

LNMC expressed that 1) more workshops should be planned to carry out this joint study; 2) Lao PDR side is willing to share data, hope China side could share more data in the future. 3) The approach of evaluate meteorological conditions should be defined and shared.

China appreciated the suggestions of the other parties, and responded as follows. 1) In April 2010, a severe drought hit the Lancang-Mekong basin, and there were suspicions that China was storing water. In fact, the dams were still under construction and did not store water in that period. At that time, Chinese government decided to provide hydrological data in dry season 2010 to make the downstream countries more prepared during the drought. The drought situation was similar in 2012-2013 dry season, but the dams supplied about 7 billion m^3 water to the downstream, which make the downstream people did not suffer from the same severe hydrological drought in 2012-2013 dry season as 2010; 2) It is good suggestion to collect daily rainfall data and flow data during the flash flood in December 2016, and the study period of this event could start from 1 December; 3)There are many meteorological stations in the Lancang River basin, we would select the typical stations to collect and share data; 4) The suggestions and concerns of the participants are noted, and further study on larger spatial or temporal scale, for example flood control cooperation during whole-basin scale flood, could be discussed in future cooperation;5) We appreciated the coordination of VNMC during the field survey of JOE. There are many potential and important cooperation opportunities in the future, now we are working on the first step which aims not at solving all the problems once in a time, but starting the cooperation and building solid foundation of future cooperation. The Lancang-Mekong Water Resources Cooperation Center has been set up, discussions on future cooperation are welcomed within this new mechanism. 6) Hope the relative parties could adhere to the proposed work schedule, start the study work first, and promote the inner procedures smoothly. 7) China side could arrange another workshop this year to further discuss this Joint Research if necessary. The Lancang River is open to the visits of downstream experts, more exchange visits are always welcomed. 8) The participants are encouraged to subjectively share what they see via medias about this field visits, help to eliminate misunderstandings on the Lancang River hydropower cascade, enhance mutual trust and deepen our friendship.

3.2 Joint Visit to the Mekong River, Nakhon Phanom Province, Thailand, 13-14 December 2017

The Joint Visit to the Mekong River in Nakhon Phanom Province of Thailand was organized by the MRC Secretariat (MRC, 2018) in a close collaboration with the Department of Water Resources through the Thai National Mekong Committee Secretariat during 13-14 December 2017 with the following objectives:

- To gain knowledge of the study area along the Mekong Stretch and its surrounding area;
- To have a better understanding of water need in the dry season and hydrological condition in the area downstream of Nam Songkhram basin, Nong Han Lake and its wetlands;
- To visit main hydrological stations on the Mekong mainstream;.and
- To visit infrastructures and command area of Nam Kam basin development project.

Twenty-seven participants of the joint visit consisted 4 staff from MRC Secretariat, 2 representatives each from Cambodia, Lao PDR, and Viet Nam, 9 officers from Thailand, 2 representatives from IWMI, and 6 officers from China. The participants had visited several places including:

- A reach of Nam Songkham tributary and a CCTV site installed with a camera feeding information to the control center under the Department of Water Resources in Bangkok;
- Mekong-HYCOS station on Nam Songkham at Ban Had Phaeng – one of major tributaries of the Mekong mainstream in Sakhon Nakhon Province;
- Suratsawadee regulator and Nong Han Lake managed by the Department of Fisheries (DOF) under an initiation of HM *King* Bhumibol Adulyadej the *Great*. Nong Han Lake is the second largest lake in Thailand which is utilized for fishery, water supply and irrigation. The operation rule of the lake and its water resources system were presented;
- Mekong-HYCOS station on Mekong river at Nakhon Phanom province and a Joint Discharge and Sediment Measurement Site (between Thailand and Lao PDR) at Nakhon Phanom city;
- Nam Kam Basin Development Project – managed by Royal Irrigation Department (RID) under an initiation of HM *King* Bhumibol Adulyadej the *Great*. The project composts of 7 regulators, 15 'Monkey Cheek' large swamps which benefits area of 165,000 Rai (about 26,400 ha);
- *Thoranit Naruemit* regulator under Nam Kam Basin Development Project, the biggest regulator located at downstream of the Nam Kam tributary.

During the Joint Visit, the participants discussed about hydrological (near real-time) stations and flow conditions. The participants had learned the flood and drought situation (cause of incidents, coverage area, and period of incidents). The participants had also observed the surrounding activities of visiting places such as agricultural practice, water storage and uses, fish farming and fishery activities, and annual crop calendar of the areas of visit. In addition, the participants had observed livelihood of people by learning about the community's involvement, expectation, and livelihood impact.

During the trip, below datasets (phase 1) were exchanged between the MRCS, its member countries, IMWI and China.

- IMWI: Daily rainfall and standard evapotranspiration time series from gridded products (e.g. CHIRPS - Climate Hazards Group InfraRed Precipitation with Station data[8] and USGS FEWS Global daily PET product) over the Lancang-Mekong Basin from 1981 to 2016.
- MRC: Daily water level and discharge data at mainstream hydrological stations upstream Kratie from 1985 to 2016; and
- MRC: Daily rainfall data at the typical meteorological stations in the Mekong Basin from December 2013 to January 2014.
- China: Monthly rainfall over the Lancang-Mekong Basin from the Global Land Data Assimilation System (GLDAS), covers the interest period from October 2009 to May 2010 and from October 2012 to May 2013

[8] http://chg.geog.ucsb.edu/data/chirps/

Figure 3.2-1 Photos during the visit at Nam Songkram Tributary

Mr. Kunpote Buatone – Director of Plan and Measures Division, Water Crisis Prevention Center was describing on CCTV site with its operation along Nam Songkham tributary and the local aquaculture (13 December 2017)

Figure 3.2-2 | Photos during the visit at Ban Had Phaeng HYCOS Station

Mr. Mongkol Lukmuang – Director of Bureau of Research Development and Hydrology was describing on near real-time monitoring system from Ban Had Pheang HYCOS Station (13 December 2017)

Figure 3.2-3 | Photos during the visit at Nong Han

Mr. Pramook Reuleauma – Director of Sakon Nakhon IFRDC was describing the Nong Han information and an initiation project to undertake the Suratsawadee regulator construction project (13 December 2017)

Figure 3.2-4 | Photos during the visit at Nakhon Phanom HYCOS Station

Mr. Mongkol was explaining on the Nakhon Phanom Station and water level during the dry and wet seasons (14 December 2017)

Figure 3.2-5 | Photos during the visit at Nakhon Phanom

Joint Discharge and Sediment Measurement Site in front of the Nakhon Phanom Police Station (14 December 2017)

Figure 3.2-6 | Field Visited at the Thoranit Naruemit regulator (14 December 2017)

4 Profile of the Lancang-Mekong Basin

4.1 General Geography

The Lancang-Mekong[9] River originates from Yushu Tibetan Autonomous Prefecture in Qinghai Province of China, and runs out of China from Xishuangbanna Dai Autonomous Prefecture in southern Yunnan Province. The Lancang-Mekong River flows through Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam, before emptying into the sea in the west of Ho Chi Minh City.

The Lancang-Mekong River ranks the 10th in the world's great rivers on the basis of mean annual flow at the mouth[10]. The Lancang-Mekong can be divided into two parts: the Upper Basin in China where the river is called the Lancang, and the Mekong Basin from Yunnan downstream from China to the Sea. The Lancang Basin covers an area of 184,895 km^2, with an annual average volume of 64 billion m^3, accounting for 20.7% of the total Lancang-Mekong Basin area[11] of 810,000 km^2 and 13.5% of the total 13.5% of the total Lancang-Mekong annual average volume of 475 billion m^3, respectively. (MRC, 2010a). A large portion of the annual flow (about 75%) occurs in just four months of the monsoon season July – October. Additionally, the difference in elevation from the source (Tibetan plateau) to the mouth of the river is 5,060 m with an average gradient of 1.04 ‰, most of the steep slope occurs along the Lancang River within the territory of China, where the river flows through steep alpine valley. Compared with the flat broad basin in the downstream, the Lancang Basin is relatively narrow.

Almost half of the total length of the Lancang-Mekong River of about 4,763[12] km is located in the territory of China. This section of the river flows through narrow areas of high mountains and deep valleys, thus, the volume of the Lancang River accounts only for 13.5% of the annual total volume. The flow regime of the river is mainly influenced by the Monsoon rains that occur every year in the downstream Southeast Asia, especially in Lao PDR, where the basin area covers mainly tropical rainforest and farmland.

The last 170 km of the Lancang River within the territory of China and the section flowing through Myanmar to the border of Thailand, the river transits from section with steep to mild slope, and flows through broad fertile valley. After leaving the territory of China, the river flows along the border of Lao PDR and Myanmar, passes through the border of Lao PDR and Thailand in the downstream of Chiang Saen.

[9] In documents of the Mekong River Commission, 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

[10] Mekong River Commission (MRC) 2005. Overview of the Hydrology of the Mekong Basin. Mekong River Commission, Vientiane, November 2005. 73 pp.

[11] The total Lancang-Mekong Basin area of 795,000 km^2 is used in MRC publications (e.g. Overview of the Hydrology of the Mekong Basin), however, China suggests the total Lancang-Mekong Basin area of 812,400 km^2. The figure 810,000 km^2 is obtained from the recent review of MRCS in 2018.

[12] The figure is from the review of the MRCS in 2018.

The Lancang-Mekong Basin can be generally divided into 6 major zones: zone one represents the Lancang Basin in China, and five zones are in the Mekong Basin, coincident with the five fluvial geomorphological reaches along the mainstream. The rationale behind the number and extent of these six reaches of the Lancang-Mekong mainstream encompasses a range of considerations, which include hydrological regime, physiography, landuse, existing, planned and potential resource developments as well as the perceived nodes along the mainstream at which there exist discernable transformations in hydrological response and where the impacts of existing and potential resource developments are likely to be detectable.

Zone 1 – Lancang River in China. The Lancang Basin is mainly characterized by steep alpine valley, located in the under-developed region with extremely inconvenient transportation and deficient natural resources, except extraordinary rich hydropower resources. Water use rate is about 3% in this area, and the water consumed is less than 1% of the total volume of the Lancang-Mekong Basin. This zone contributes about 13.5% volume of the Lancang-Mekong River. The runoff normally comes from rainfall, snowmelt and groundwater. This zone has distinguishing wet season and dry season. The dry season lasts from November to April, during which the volume mainly depends on the snowmelt and groundwater. Additionally, there are currently six hydropower projects on the mainstream of the Lancang River, which could generally increase the volume of the Lancang River by 70% in the dry season and reduce it by 30% in the rainy season. This helps flood mitigating and drought relieving with a proper regulation.

Zone 2 – Chiang Saen to Vientiane/Nong Khai. The additional hydrological contributions to it are generated almost entirely in Lao PDR. This reach is well defined physiographic sub-region of the lower basin being almost entirely mountainous and covered with natural and mostly undisturbed land cover. There is little scope for extensive agricultural development comparative in scale to that further downstream nor are there any plans for any significant water resources developments. Pre-feasibility and feasibility studies of the hydropower potential here, for example, has centred upon small run of river schemes (no regulation beyond diurnal pondage). Although this zone could hardly be described as pristine, the hydrological response from it is certainly the most natural and undisturbed within the basin. In addition, however, it is at the downstream boundary of this zone that virtually every relevant facet of the basin starts to undergo rapid transition.

Zone 3 – Vientiane/Nong Khai to Pakse. The upstream boundary of Zone 3 is the point at which the broader picture of Mekong hydrology changes from one dominated in both wet and dry seasons by the Zone 1 to one increasingly influenced by the contributions from the large left bank tributaries in Lao PDR, namely the Nam Ngum, Nam Theun, Nam Hinboun, Se Bang Fai, Se Bang Hieng and Se Done rivers. Also entering the mainstream within this zone extending to Pakse, is the Mun/Chi system from the right bank and Thailand. The Mun and Chi Rivers are highly developed low relief, agricultural basins with comparatively low runoff potential and significant reservoir storage for dry season irrigation. The left bank Lao tributaries are under steady development in terms of agricultural water demand and hydropower development.

Zone 4 – Pakse to Kratie. The major hydrological contributions to the mainstream in this reach coming from the Sekong, Sesan and Srepok catchments, jointly the largest hydrological sub- component of the basin. Over 25% of the mean annual flow volume on the Mekong mainstream at Kratie originates from these three river basins, which are therefore a crucial element in the hydrological dynamics of this part of the system, not least with respect to the Tonle Sap Lake flow reversal.

Zone 5 – Kratie to Phnom Penh. This reach encompasses the hydraulic complexities of the Cambodian floodplain, the Tonle Sap Lake and River. By this stage over 95% of the total flow has already entered the Mekong system and the balance of emphasis moves from hydrology and water discharge to the critical assessment of water level, overbank storage and flooding and the hydrodynamics that determine the timing, duration and volume of the seasonal flow reversal into and out of the Tonle Sap Lake.

Zone 6 – Phnom Penh to the sea. This stretch defines lower Cambodia, the flow bifurcations and the delta region in Viet Nam, with the total volumes of flow entering the latter observed as the sum of those recorded at Tan Chau and Chau Doc.

4.2 Existing Hydropower Dams in China

The construction of dams (for hydropower and irrigation) within the Lancang-Mekong River Basin started as early as the 1950s. However, most of these dams have been located on tributaries of the Lancang-Mekong River. The first major dam on the main stem of Lancang River was the Manwan reservoir commissioned in 1993 and the most recent is the Miaowei dam which was commissioned in 2017 with a capacity of 1400 MW (**Figure 4.2-1** and **Table 4.2-1**). To date the largest hydropower dam on the Lancang-Mekong River is the Nuozhadu dam which was commissioned in 2014. The Xiaowan Reservoir and Nuozhadu Reservoir have especially the multi-year regulating capacity, with regulating storage of 21.2 billion m^3 in total. By scientifically operating and regulating, the Lancang River cascade reservoirs are capable to balance the water discharge/volume between the wet season and dry season, benefiting the Mekong River on the aspects of flood control, irrigation, navigation and so on.

Table 4.2-1 | Characteristics of hydropower dams constructed along the main stem of the Langcang-Mekong River Basin.

Hydropower Project	Commission (Year)	Installed capacity (MW)	Mean annual energy GW	Height (m)	Total storage (km^3)	Active storage (km^3)
Manwan	1993	1670	7784	132	0.50	0.12
Dachaoshan	2001	1350	7021	111	0.94	0.36
Jinghong	2008	1750	7858	108	1.14	0.31
Xiaowan	2009	4200	18885	294.5	14.91	9.90
Gongguoqiao	2011	900	4041	105	0.35	0.05
Nuozhadu	2012	5850	23912	261.5	23.70	11.34
Miaowei	2017	1400	5999	131.3	0.75	0.17

Figure 4.2-1 | Map of the Lancang-Mekong Basin.

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

5 Comparative analysis of the droughts of 2009-2010 and 2012-2013

5.1 Research Scope

The Lancang-Mekong Basin experienced a severe drought from October 2012 to April 2013. The drought caused extensive damages to water supply, agricultural production and livelihood of people. This drought was similar in terms of spatial distribution and magnitude to the drought that occurred between October 2009 and April 2010. The main hydrological difference between these two droughts is likely caused by the Xiaowan Dam that was not completed and could not store water during 2009-2010, but was operational by July 2010 and already achieved its operational water storage target, releasing additional water from November 2012 to April 2013. Based on SPI, SRI and hydrological frequency analysis, this study compares the two drought events from the meteorological and hydrological perspective, and analyzes the impact of water supplement from Lancang hydropower cascade on the hydrological process of the Mekong River during the dry seasons of 2009-2010 and 2012-2013.

Main hydrological stations on mainstream of Lancang-Mekong river is shown in Figure 5.1-1. Jinghong Hydropower Plant is the last level of Lancang hydropower cascade, so Jinghong Station is selected as the representative hydrological station of Lancang River Basin to carry out relevant analysis. In order to maintain the consistency of the study, seven hydrological stations in the main stream of the Mekong River were selected to carry out the streamflow related analysis, because the flow data series of the Kratie hydrological stationis shorter than that of the other seven stations in the main stream of the Mekong River. Chiang Saen, Mukdahan and Stung Treng stations were selected as representative stations along the Mekong River.

Table 5.1-1 | Information of hydrological stations in Lancang-Mekong River

Number	Name	Latitude	Longitude	Country	Data Availability (Daily Discharge)
1	Jing Hong	22.033	100.789	China	Flood season of 2002-2018; Dec.2013-Jan.2014 Dec. 1, 2015-May 15, 2016
2	Chiang Saen	20.274	100.089	Thailand	1985-2016
3	Luang Prabang	19.893	102.134	Laos	1985-2016
4	Nong Khai	17.881	102.732	Thailand	1985-2016
5	Nakhon Phanom	17.425	104.774	Thailand	1985-2016
6	Mukdahan	16.583	104.733	Thailand	1985-2016
7	Pakse	15.100	105.813	Laos	1985-2016
8	Stung Treng	13.533	105.950	Cambodia	1985-2016
9	Kratie	12.481	106.018	Cambodia	2005-2016

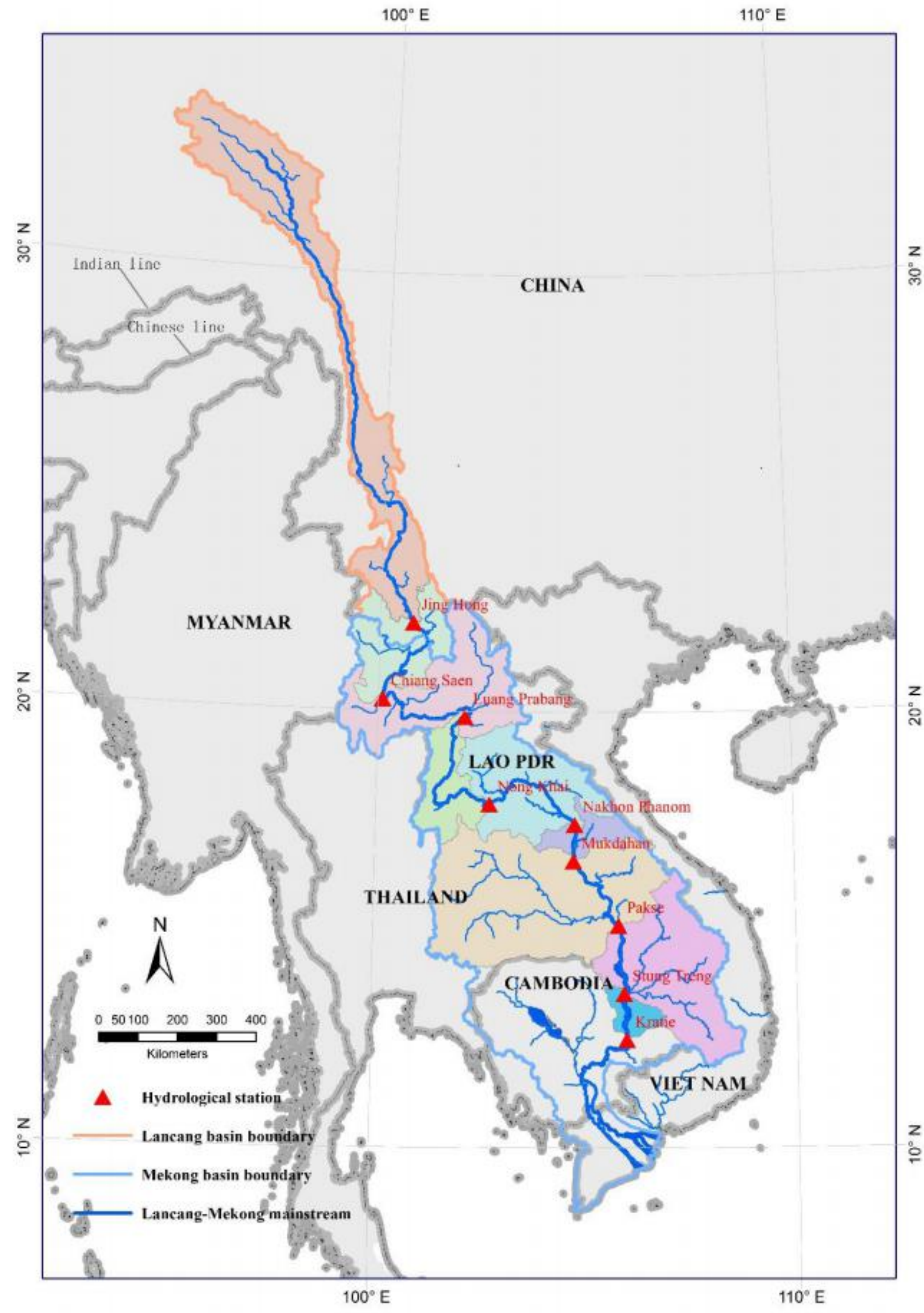


Figure 5.1-1 | Hydrological stations and corresponding drainage area on mainstream of Lancang-Mekong river.

5.2 Hydrological Process during the Two Events

Based on the daily flow data from 1985 to 2016 provided by the Mekong River Commission Secretariat, the flow series of Chiang Saen, Luang Prabang, Nong Khai, Nakhon Phanom, Mukdahan and Stung Treng are shown in Figure 5.2-1 to Figure 5.2-7. As can be seen from the chart, compared with the drought in 2009-2010, the flow of each station during the dry season of 2012-2013 is relatively higher.

As the most upstream hydrological station in the Mekong River Basin, Chiang Saen Station is very important to understand the flow characteristics of the Lancang River and its impact on the downstream. The flow of Chiang Saen Station from January to March 2013 was significantly higher than that of the same period in 2010. The flow of other stations in dry season of 2012-2013 is also significantly higher than that in dry season of 2009-2010.

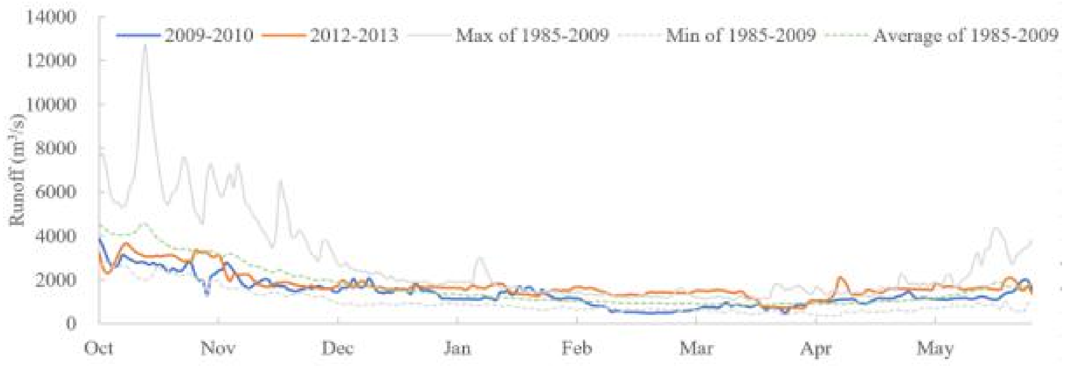


Figure 5.2-1 | Hydrological process at Chiang Saen Station during the two drought events.

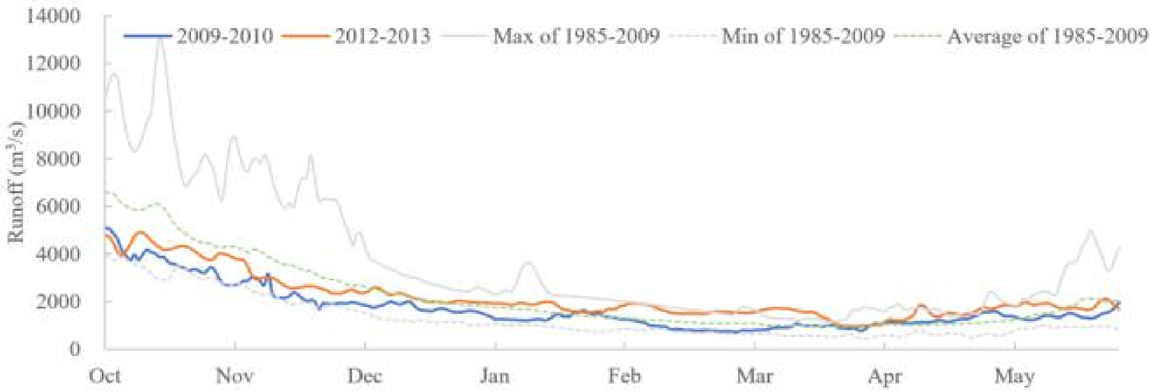


Figure 5.2-2 | Hydrological process at Luang Prabang Station during the two drought events.

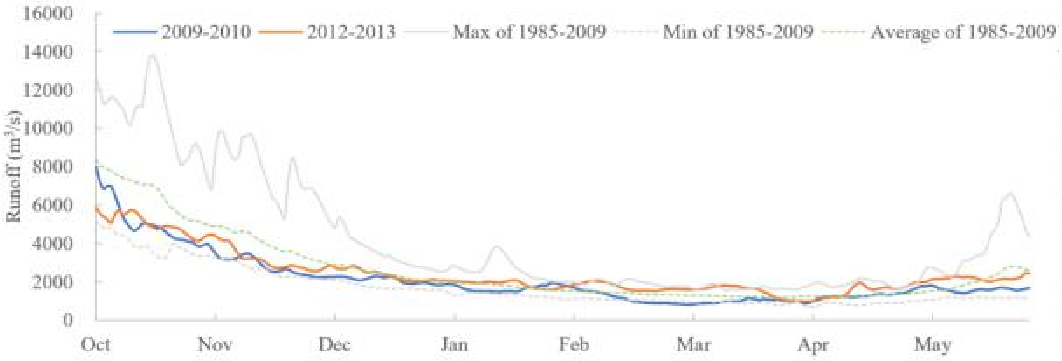


Figure 5.2-3 | Hydrological process at Nong Khai Station during the two drought events.

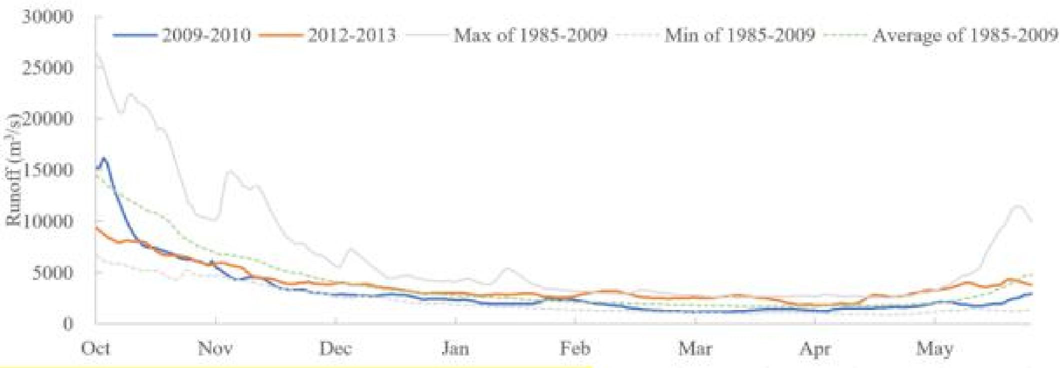


Figure 5.2-4 | Hydrological process at Nakhon Phanom Station during the two drought events.

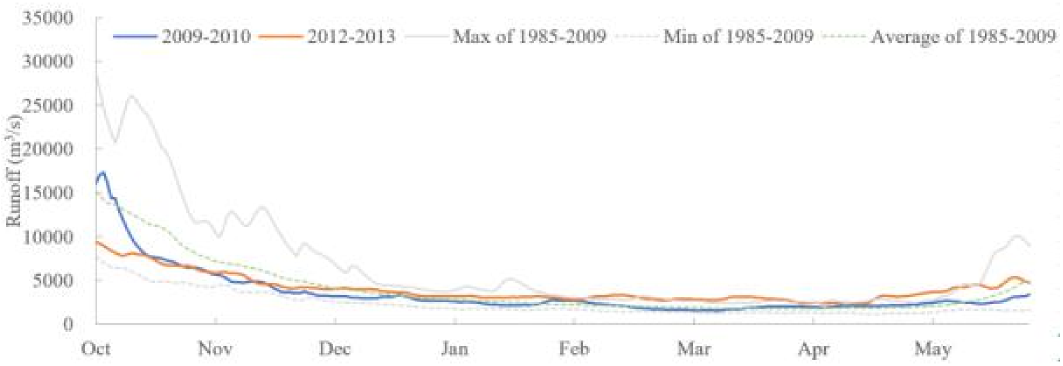


Figure 5.2-5 | Hydrological process at **Mukdahan** Station during the two drought events.

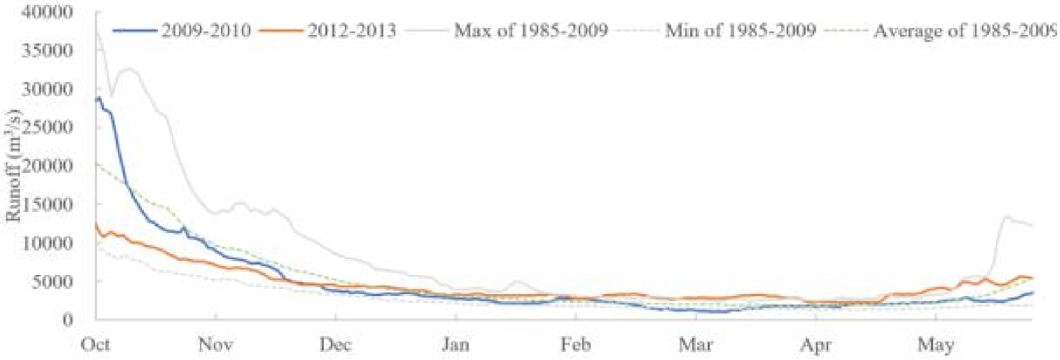


Figure 5.2-6 | Hydrological process at **Pakse** Station during the two drought events.

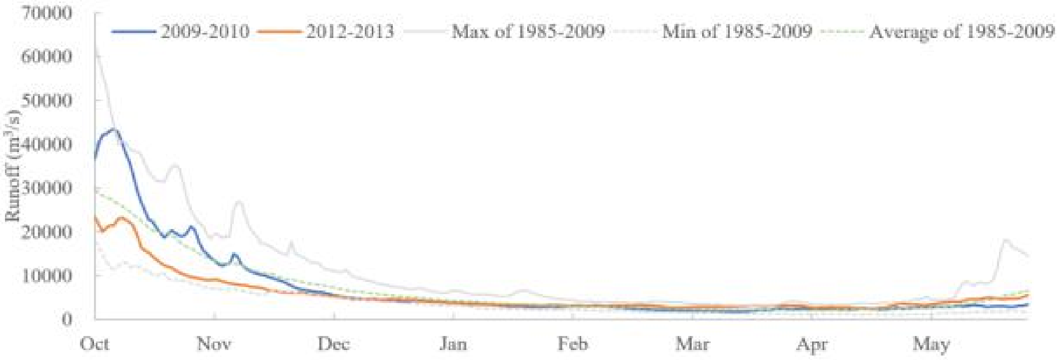


Figure 5.2-7 | Hydrological process at **Stung Treng** Station during the two drought events.

5.3 Drought Analysis

5.3.1 Data

(1) Historical long-sequence rainfall data of the Mekong River Basin in the recent 70 years (1948-2015) was collected and compiled on the basis of the GLDAS（Global Land Data Assimilation System）global precipitation product. GLDAS is a full-coverage and high-resolution data set based on global observation data and simulations of four land surface process models. Data assimilation was applied to achieve the global high-resolution data set (2.5° to 1km). The sequence length of date used in this study is 1948-2015, spatial resolution is 0.25°×0.25°, and all land networks in the world are covered.

(2) The historical long-sequence section flow data of major hydrological stations of Chiang Saen, Luang Prabang, Nong Khai, Nakhon Phanom, Mukdahan, Pakse, Stung Treng on mainstream Mekong River was collected from Mekong River Commission Secretariat. The sequence length is 1985-2016, and temporal resolution is daily-scale observation.

5.3.2 Methodology

In this project, we established the Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI), and carried out hydrological frequency analysis as indicators for monitoring and diagnosis of different types of drought and analyze the characteristics of drought, on different scales and of different types, in the Mekong River, from meteorological and hydrological perspectives.

(1) Definition and calculation of SPI

Generally speaking, precipitation abides by skewed distribution rather than normal distribution. In drought monitoring and evaluation, Γ distribution probability is usually adopted to describe the variation of precipitation. The Standardized Precipitation Index (SPI), for measuring the excess and deficit of precipitation on various temporal scales, is a widely adopted index for drought diagnosis. Γ distribution probability is adopted to describe precipitation in the SPI calculation; then, normal standardization of skewed probability distribution is conducted; finally, 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. SPI formula is:

$$\mathrm{SPI} = \mathrm{S}\left(t - \frac{(c_2 t + c_1)t + c_0}{[(d_3 t + d_2)t + d_1]t + 1.0}\right) \quad (3.2\text{-}1)$$

$$t = \sqrt{\ln \frac{1}{G(x)^2}} \quad (3.2\text{-}2)$$

In specific, x is precipitation sample value; S is the positive and negative coefficients of probability density; c0, c1, c2 and d1, d2, d3 are calculation parameters of the simplified approximation analysis formula for converting Γ distribution probability into cumulative frequency. c0=2.515517, c1=0.802853, c2=0.010328, d1=1.432788, d2=0.189269 and d3=0.001308. G(x) is rainfall distribution probability related to Γ function. According to the probability density integral formula of Γ function is:

$$G(x) = \frac{2}{\beta^{\gamma}\Gamma(\gamma_0)} \int_0^x x^{\gamma-1} e^{-x/\beta} dx, \qquad x > 0 \quad (3.2\text{-}3)$$

When G(x) > 0.5, S = 1; when G(x) ≤ 0.5, S = -1.

Table 5.3-1 is gradation of Drought based on SPI by WMO (World Meteorological Organization).

Table 5.3-1 | SPI-Based Gradation of Drought.

Category	SPI	Severity of event
Mild dryness	(-1.0, 0)	1 in 3 yrs
Moderate dryness	(-1.5,-1.0)	1 in 10 yrs

Severe dryness	(-2.0,-1.5)	1 in 20 yrs
Extreme dryness	≤-2.0	1 in 50 yrs

(2) Definition and calculation of SRI

By reference to the calculation principle of SPI, the Standardized Runoff Index (SRI) was proposed. Based on long-sequence measurement or simulated monthly runoff calculation, SRI measures effectively runoff deficit relative to multi-year average runoff, expresses the probability of occurrence of the cross-section runoff of a given period in the same period in history, and is used in hydrological drought diagnosis and evaluation on and above monthly scale.

Similar with the SPI-based gradation of drought, drought is also graded with SRI≤0 being the standard of judging hydrological drought, as shown in Table 5.3-1.

(3) Hydrological Frequency Analysis

Based on 32-year (1985-2016) long time series of flow data, the minimum daily average flow, minimum monthly average flow and minimum 3-month average flow during the two drought events (December to May) was calculated and the corresponding frequency was calculated by Pearson-III Frequency Curve Fitting.

5.3.3 Meteorological Drought

Based on the long-sequence monthly precipitation data for 1948-2015 from GLDAS, The one-month, three-month, six-month and twelve-month standardize precipitation indexes (SPI1, SPI3, SPI6 and SPI12) was respectively calculated to depict the short-term and long-term meteorological drought in the Lancang-Mekong River Basin. Based on the SPI calculation results on various temporal scales, we revealed the spatio-temporal characteristics of meteorological drought happened in 2009-2010 and 2012-2013 in the Lancang-Mekong River Basin. To carry out comparison study with the hydrological drought, the study area of the SPI statistical work is partitioned by drainage area of the hydrological stations (as shown in Figure 5.1-1).

(1) Inter-annual Variation

Figure 5.3-1 to Figure 5.3-4 demonstrate the inter-annual variation characteristics of SPI on different temporal scales (SPI1, SPI3, SPI6, SPI12) between 1948 and 2015 for drainage area of the main hydrological stations. Figure 5.3-1 and Figure 5.3-2 show that rainfall in the drainage areas of Jinghong station and Chiang Saen station is characterized by alternation of abundant and deficit, and there is no obvious trend. While that of Mukdahan station and Stung Treng station characterized by a slightly descending trend, in specific, the trend in 2010-2015 is obvious.

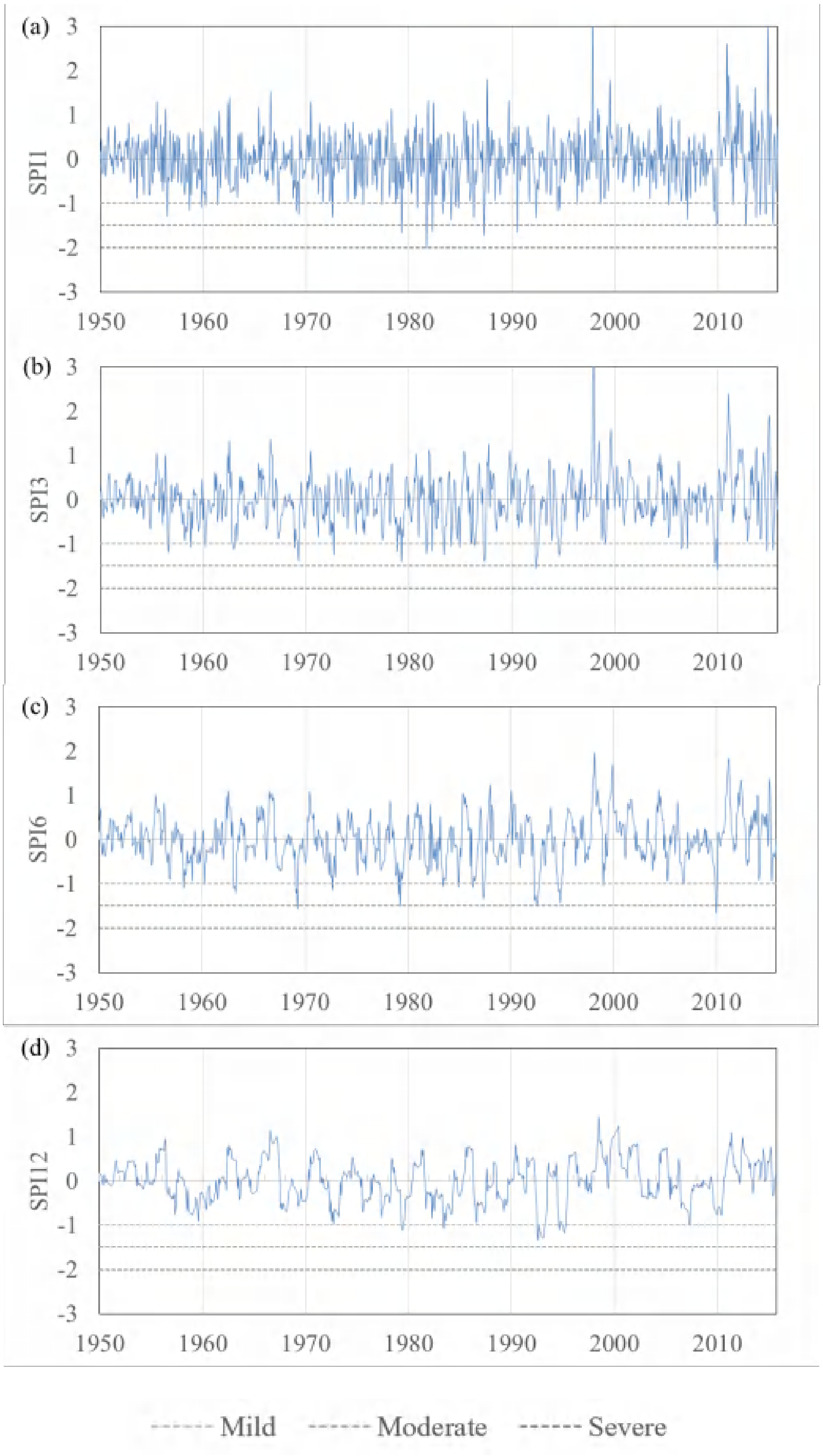


Figure 5.3-1 | SPI sequences on various temporal scales of Jinghong subbasin. (a) SPI1; (b) SPI3; (c) SPI6; (d) SPI12.

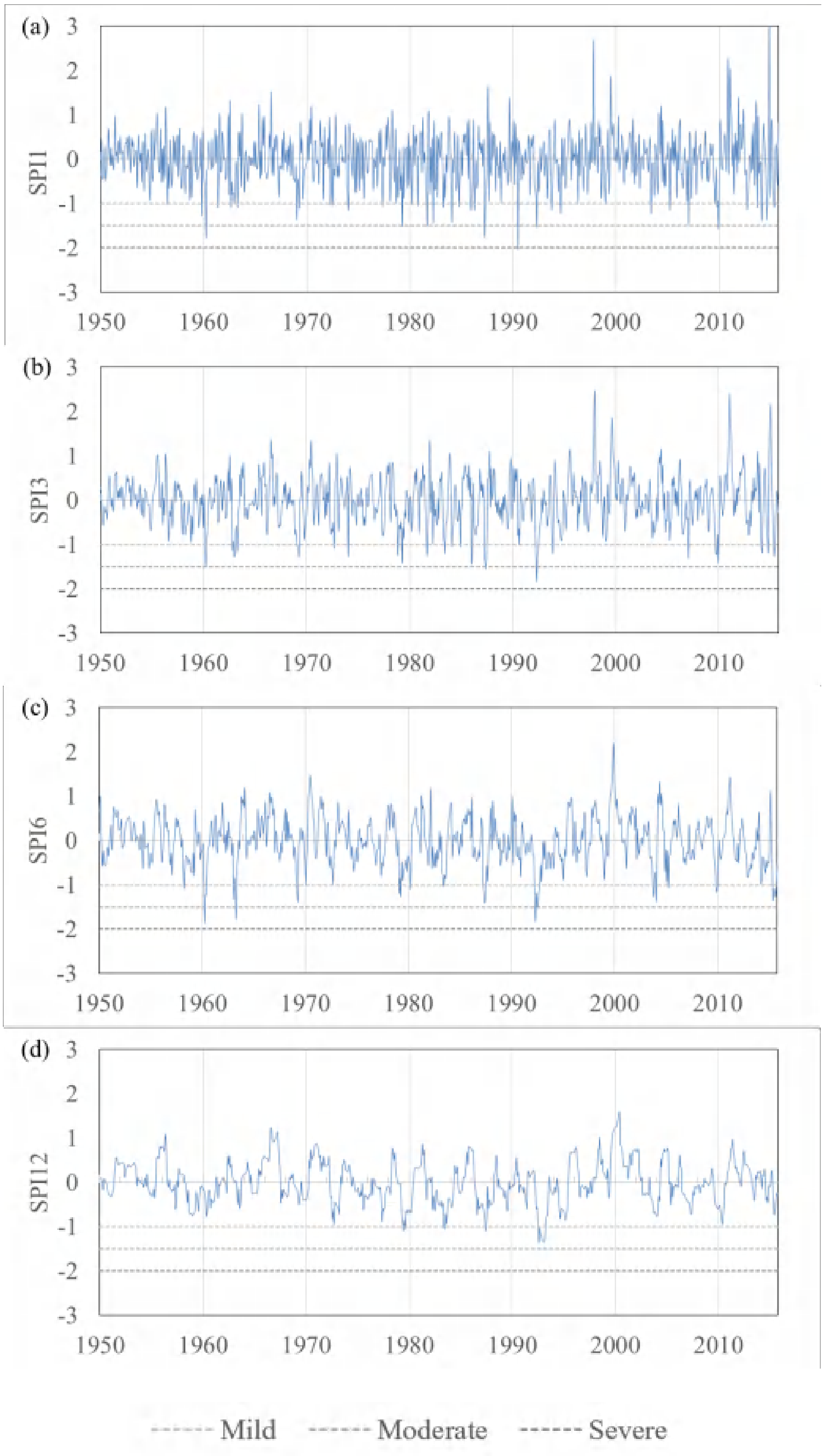


Figure 5.3-2 | SPI sequences on various temporal scales of **Chiang Saen** subbasin. **(a) SPI1; (b)** SPI3**; (c)** SPI6**; (d)** SPI12.

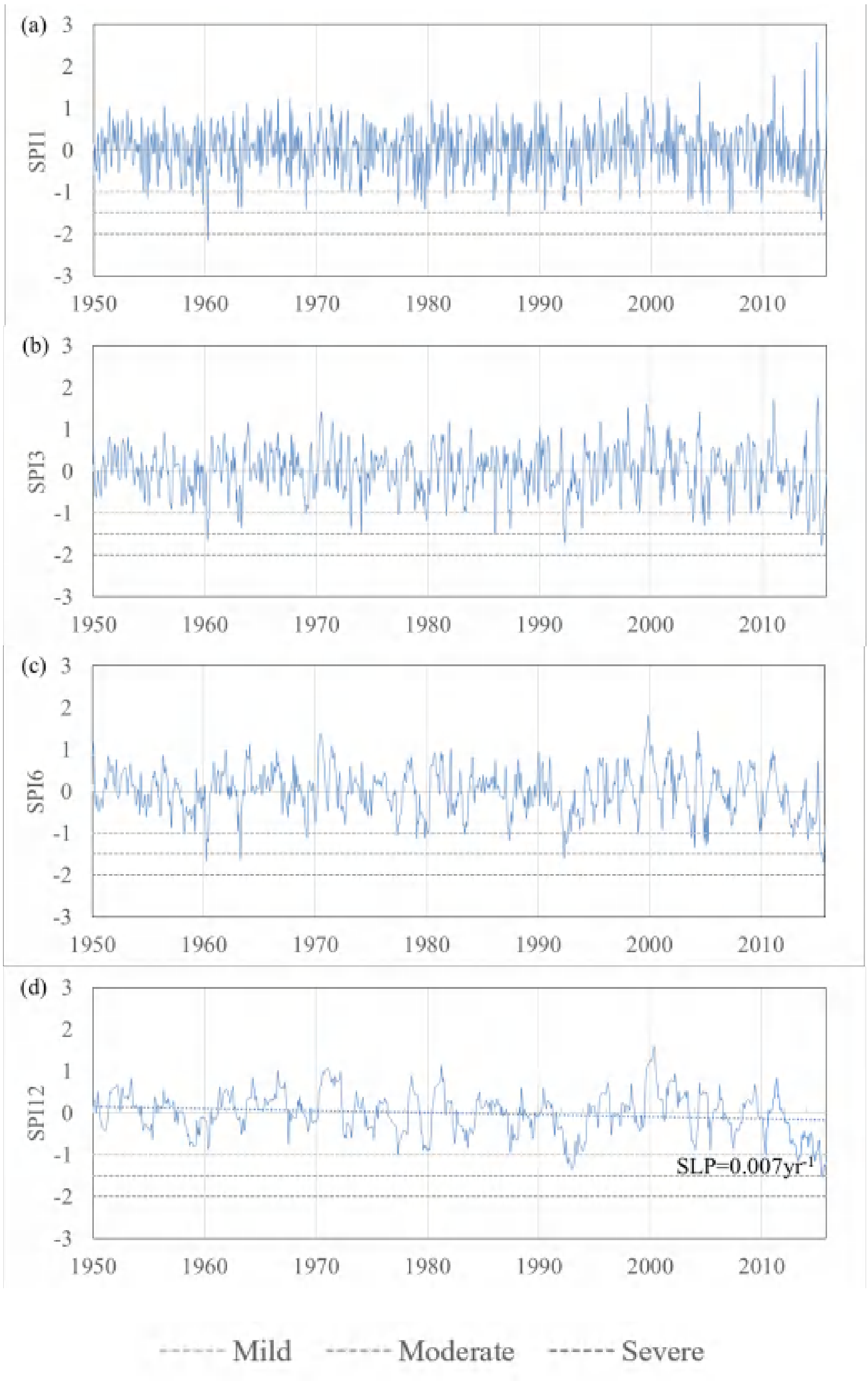


Figure 5.3-3 | SPI sequences on various temporal scales of **Mukdahan** subbasin. **(a) SPI1; (b)** SPI3**; (c)** SPI6**; (d)** SPI12.

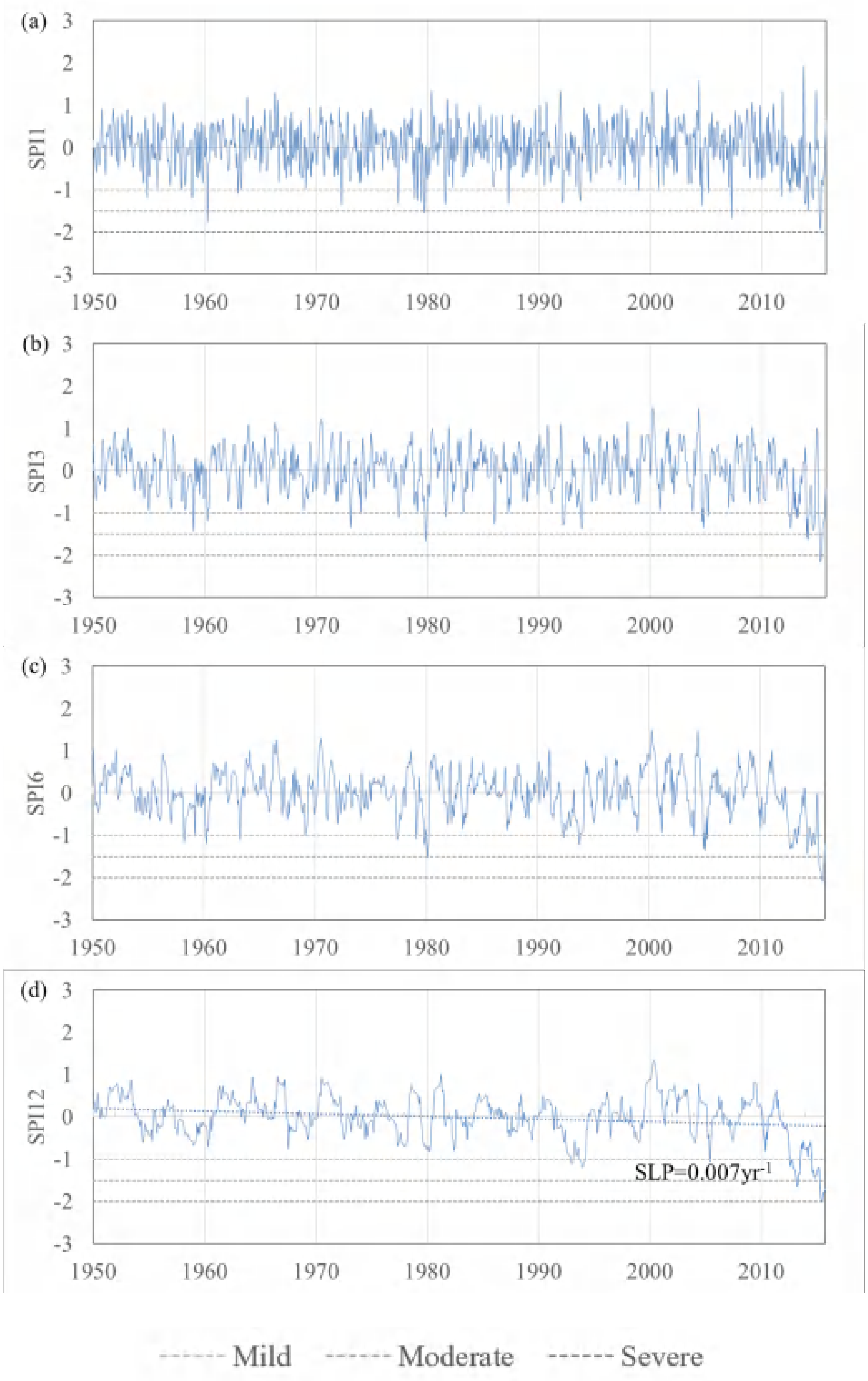


Figure 5.3-4 | SPI sequences on various temporal scales of **Stung Treng** subbasin. **(a) SPI1; (b)** SPI3; **(c)** SPI6; **(d)** SPI12.

(2) Temporal and spatial distribution of the two droughts

The monthly sequences of SPI during the 2009-2010 and 2012-2013 dry season on drainage areas of the main hydrological stations on Lancang-Mekong River is shown in Figure 5.3-5 to Figure 5.3-8.

Figure 5.3-5 demonstrates that, during the two droughts, the watershed above Jinghong station experienced relatively low rainfall before March, of which moderate and severe droughts lasted for about three months; from March to May, rainfall returned to normal or more. When the analysis scale was extended to three months (SPI3), the drought reached the severe level in February 2010, and the drought reached the moderate level in January 2013. When the analysis scale was 6 months (SPI6), the SPI6 values of the two droughts in May (i.e. the total rainfall from December to May) were close to the normal state, and the SPI6 values in April (i.e. the total rainfall from November to April) were close to the normal state in 2010 and light drought in 2013.

From the SPI sequence of the catchment area of the Chiang Saen station during the two drought events in Figure 5.3-6, we can see that the drought in 2009-2010 reached severe level in February, and the drought in 2012-2013 reached moderate level in November; the rainfall in December-March of 2009-2010 was less than that of 2012-2013; the SPI of the two drought events in January, March and May was close, belonging to light level or no drought; when the analysis scale was extended to 6 month, the SPI6 values of the two droughts in May (i.e. the total rainfall from December to May) were close to the normal state, and the SPI6 values in April (i.e. the total rainfall from November to April) were close to the normal state in 2010 and light level in 2013.

From the SPI sequence of the catchment area of the Mukdahan station and Stung Treng station during the two drought events in Figure 5.3-7 and Figure 5.3-8, we can see that they demonstrate similar characteristics. Overall, the drought in 2012-2013 is more severe than that in 2009-2010. The results of 6-month scale statistics show that most of the dry season in 2012-2013 belongs to mild/moderate drought, and most of the dry season in 2009-2010 belongs to mild drought.

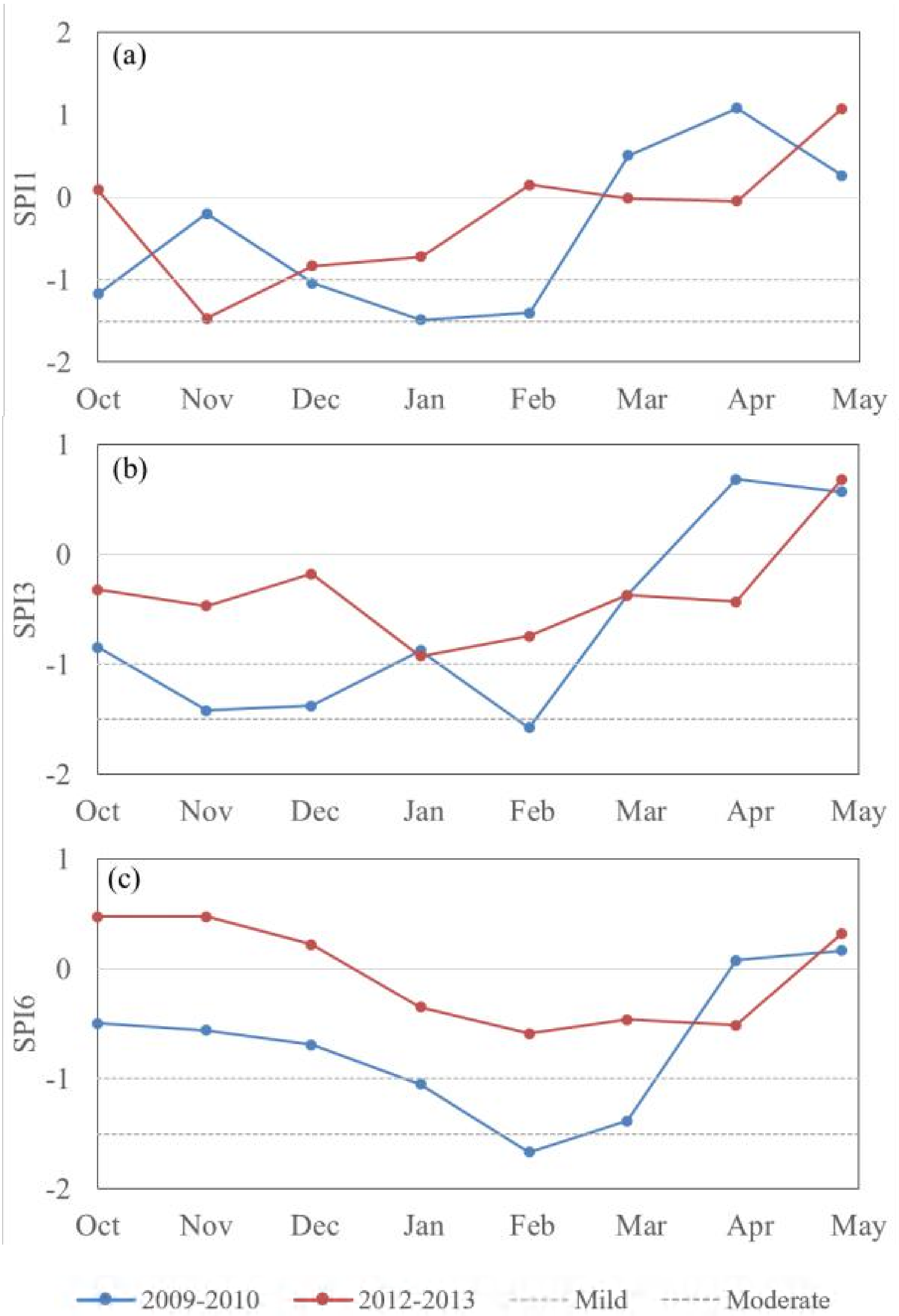


Figure 5.3-5 | Monthly SPI sequence of Jinghong subbasin during dry season of 2009-2010 and 2012-2013. (a) SPI1; (b) SPI3; (c) SPI6.

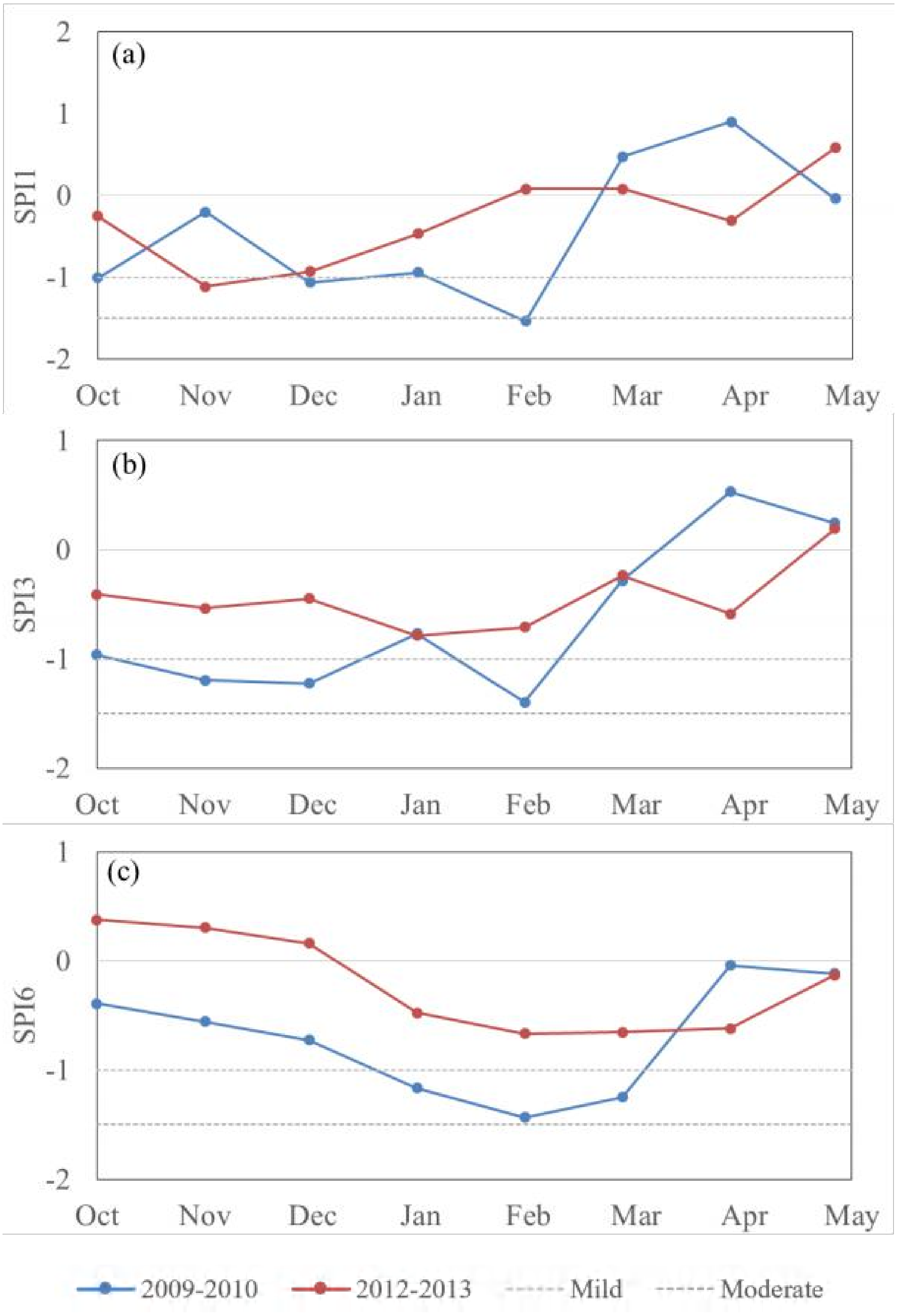


Figure 5.3-6 | Monthly SPI sequence of Chiang Saen subbasin during dry season of 2009-2010 and 2012-2013. (a) SPI1; (b) SPI3; (c) SPI6.

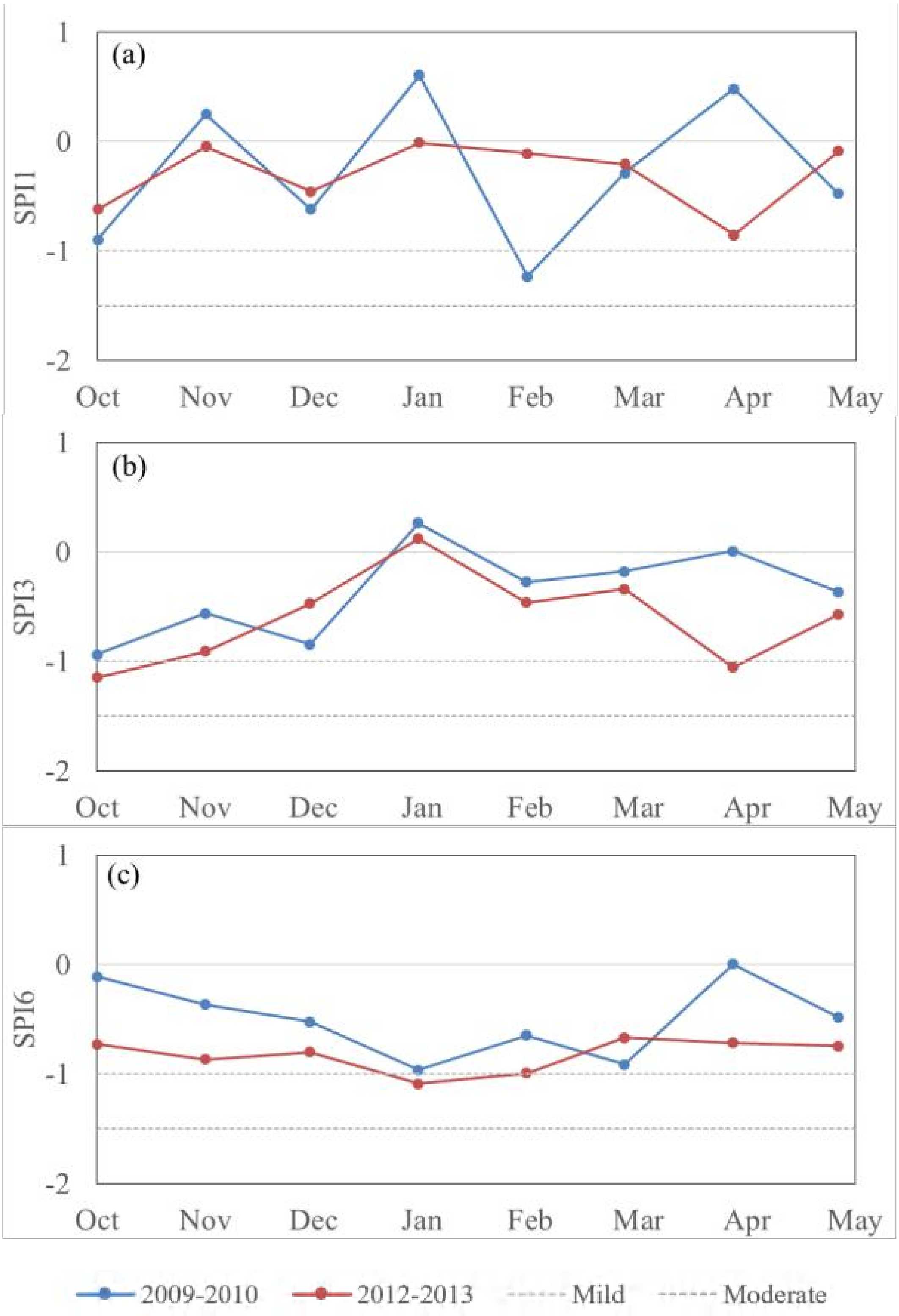


Figure 5.3-7 | Monthly SPI sequence of Mukdahan subbasin during dry season of 2009-2010 and 2012-2013. (a) SPI1; (b) SPI3; (c) SPI6.

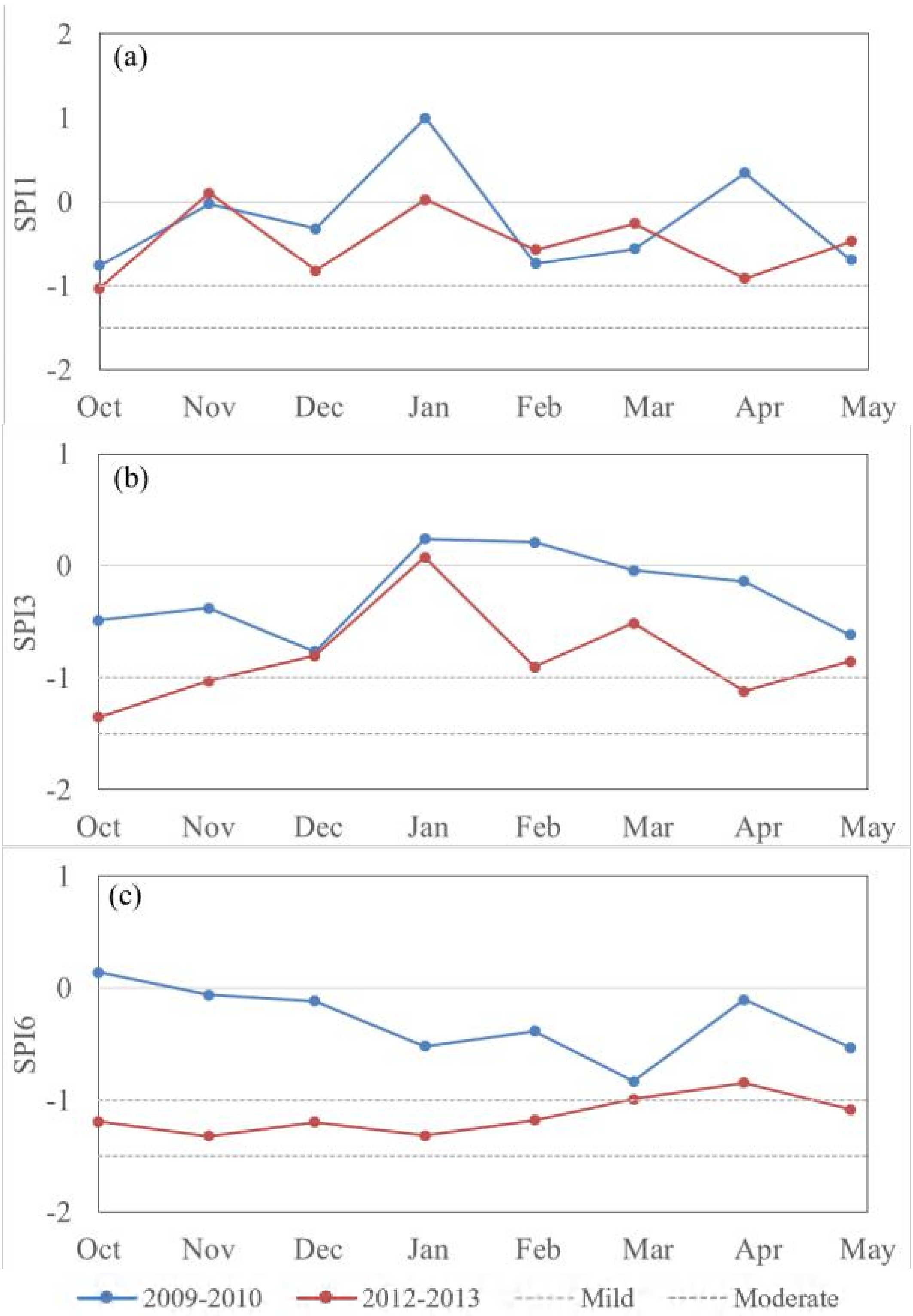


Figure 5.3-8 | Monthly SPI sequence of Stung Treng subbasin during dry season of 2009-2010 and 2012-2013. (a) SPI1; (b) SPI3; (c) SPI6.

The SPI6 results on catchment area of Lancang-Mekong main stream hydrological stations in dry season of 2009-2010 and 2012-2013 is shown in Table 5.3-2, Table 5.3-3, Figure 5.3-9 and Figure 5.3-10. Statistical data from December to May show that SPI decreases from upstream to downstream above the Pakse station, and the drought severity of the two drought events reaches moderate level in 2012-2013 and mild level in 2009-2010. Statistical data from November to April show that the Lancang-Mekong River Basin is basically mild drought in 2012-2013, and the rainfall in the basin is close to normal in 2009-2010. The spatial distribution of SPI6 in April and May of 2010 and 2013 is shown in Figure 5.3-11 and Figure 5.3-12.

Table 5.3-2 | The SPI6 result on catchment area of Lancang-Mekong main stream hydrological stations in dry season of 2009-2010 and 2012-2013 (December to May).

	Jinghong	Chiang Saen	Luang Prabang	Nong Khai	Nakhon Phanom	Mukdahan	Pakse	Stung Treng	Kratie
2009-2010	0.167	-0.119	-0.296	-0.374	-0.469	-0.481	-0.588	-0.529	-0.529
2012-2013	0.317	-0.129	-0.523	-0.616	-0.725	-0.741	-0.850	-1.084	-1.115

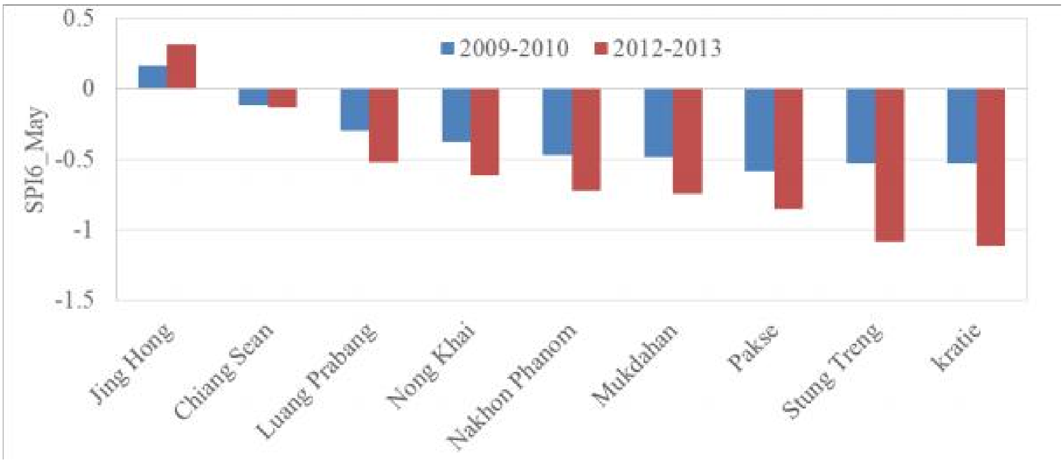


Figure 5.3-9 | The SPI6 result on catchment area of Lancang-Mekong main stream hydrological stations in dry season of 2009-2010 and 2012-2013 (December to May).

Table 5.3-3 | The SPI6 result on catchment area of Lancang-Mekong main stream hydrological stations in dry season of 2009-2010 and 2012-2013 (November to April).

	Jinghong	Chiang Saen	Luang Prabang	Nong Khai	Nakhon Phanom	Mukdahan	Pakse	Stung Treng	Kratie
2009-2010	0.076	-0.040	-0.008	-0.030	0.004	0.006	-0.106	-0.104	-0.104
2012-2013	-0.514	-0.618	-0.657	-0.631	-0.682	-0.712	-0.593	-0.846	-0.858

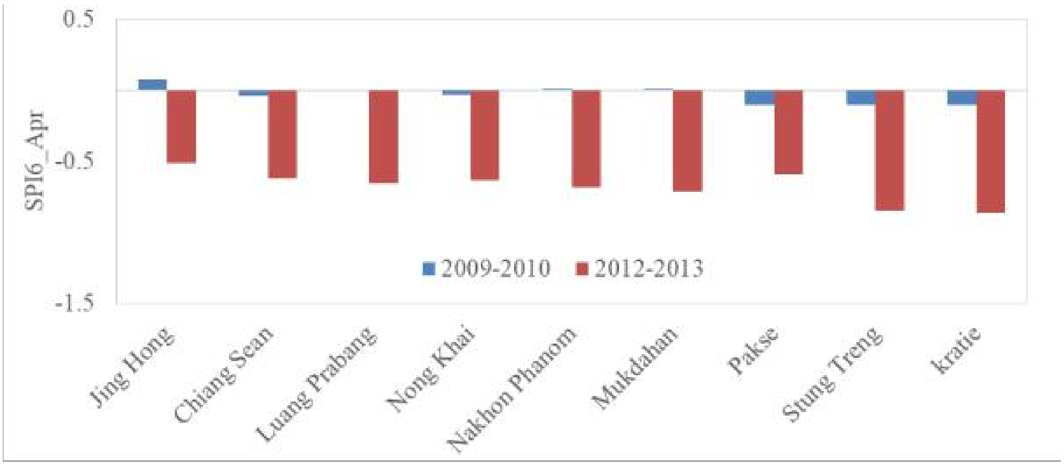


Figure 5.3-10 | The SPI6 result on catchment area of Lancang-Mekong main stream hydrological stations in dry season of 2009-2010 and 2012-2013 (November to April).

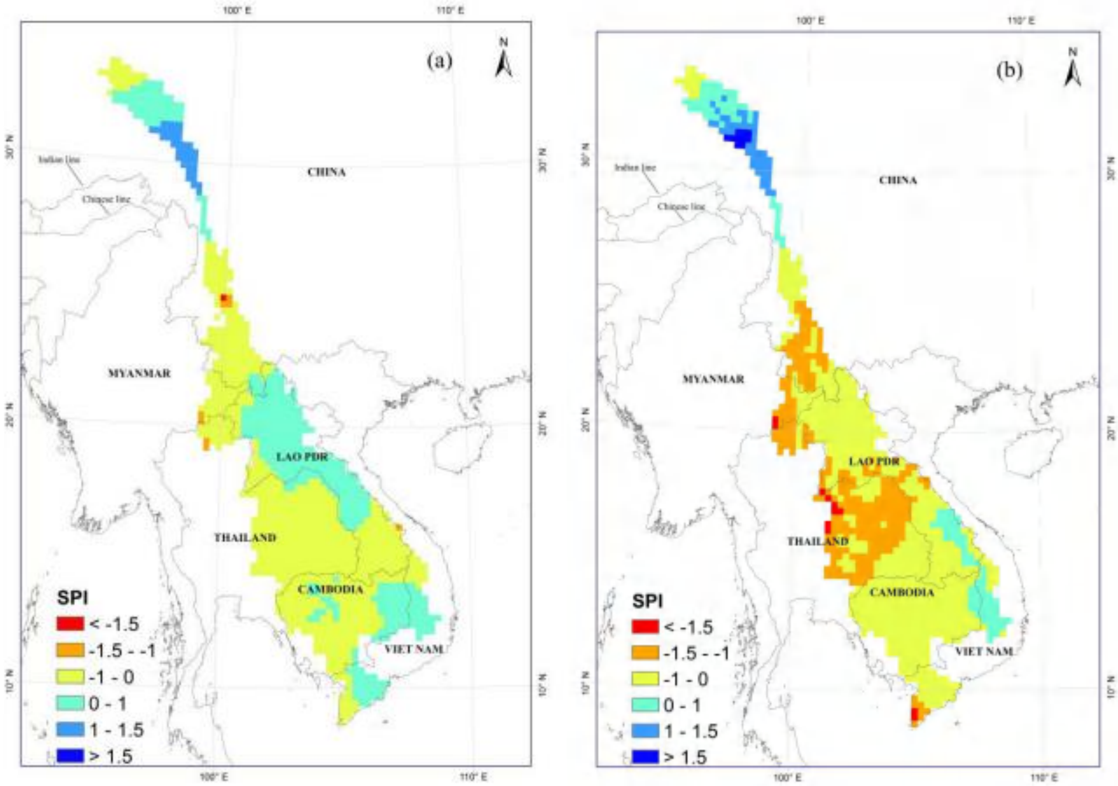


Figure 5.3-11 | Spatial distribution of SPI6 in dry season of 2009-2010 in Lancang-Mekong River Basin. (a) SPI6_Apr means based on precipitation data during November 2009 and April 2010; (b) SPI6_May means based on precipitation data during December 2009 and May 2010.

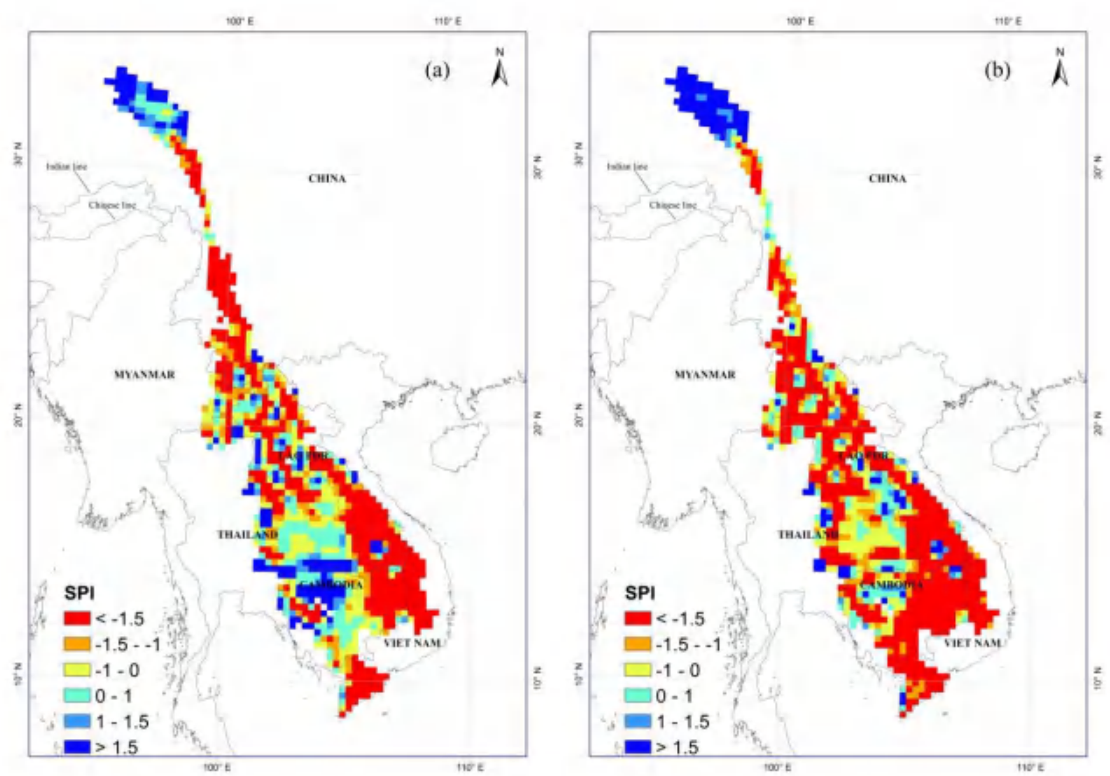


Figure 5.3-12 | Spatial distribution of SPI6 in dry season of 2012-2013 in Lancang-Mekong River Basin. (a) SPI6_Apr means based on precipitation data during November 2012 and April 2013; (b) SPI6_May means based on precipitation data during December 2012 and May 2013.

5.3.4 Hydrological Drought

(1) SRI

Three hydrological stations, Chiang Saen station, Mukdahan station and Stung Treng station, were selected to represent the hydrological characteristics along the main stream and to analyze the temporal and spatial characteristics of dry season hydrological drought in the main stream of the Mekong River. Based on the daily runoff from January 1, 1985 to December 31, 2016, the monthly average cross-section runoff of each station from January 1985 to December 2016 was calculated. Based on the monthly runoff series of 32 years (1985-2016), the Standardized Runoff Index for three-month and six-month time scale (SRI3 and SRI6) were calculated respectively, which were used to analyze the hydrological drought severity of each station in dry season at various time scales.

Figure 5.3-13 to Figure 5.3-15 demonstrate the SRI sequences at Chiang Saen station, Mukdahan station and Stung Treng station at three months and six months time scale. From Figure 5.3-13, it can be seen that the SRI value of Chiang Saen station shows an obvious upward trend, indicating that the severity and frequency of hydrological drought in dry season of Chiang Saen station are significantly reduced. From the perspective of inter-annual variation, after 2013, Chiang Saen station has been in the stage of high flow (SRI value reaching or exceeding 1.0), and no drought has occurred. Within the analysis data range, the late 20th century was the most serious period of hydrological drought at Chiang Saen station.

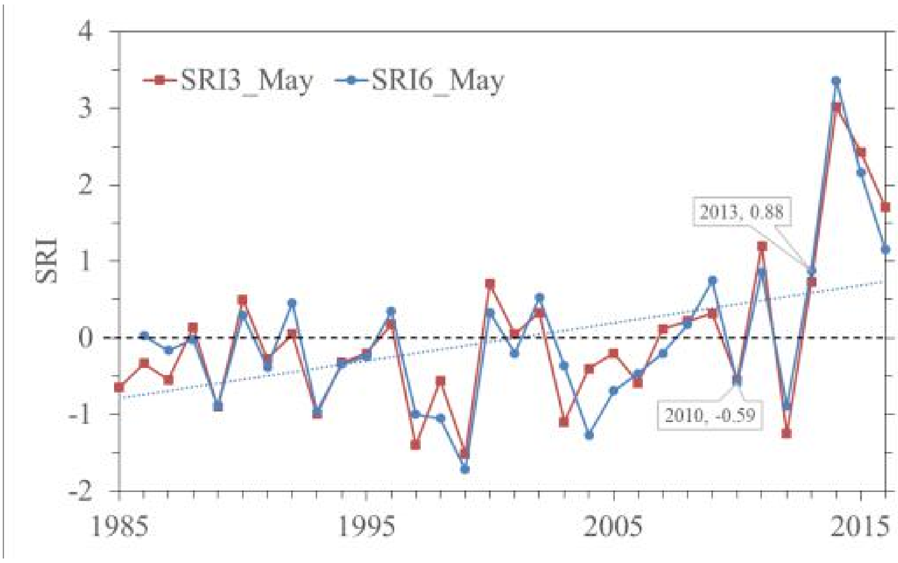


Figure 5.3-13 | SRI sequences at Chiang Saen station. (SRI6_May means based on 6-month precipitation from December to May; SRI3_May means based on 3-month precipitation from March to May).

Similar to the Chiang Saen station, the SRI sequence of Mudahan station shows an obvious upward trend, with a ratio of about 0.08/year (see Figure 5.3-14), indicating that the severity and frequency of hydrological drought have decreased significantly. In terms of inter-annual variation, the years with low flow in dry season are mainly concentrated before 2000, and the SRI values of the station are close to -1.5 in 1987 and early 1989, resulting in severe hydrological drought. In contrast, the section runoff of the station is in the stage of abundant in the dry season after 2000, in which the SRI value of the station is close to 2.0 in 2014 and 2015.

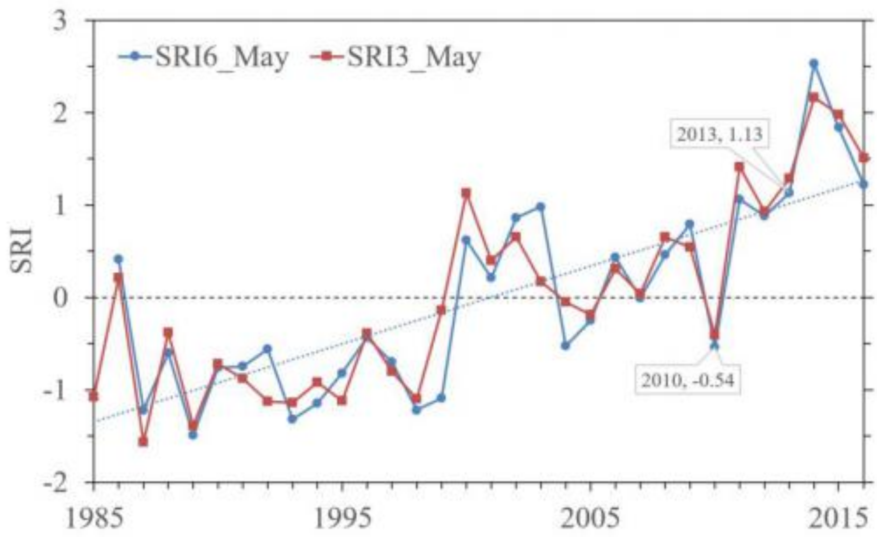


Figure 5.3-14 | SRI sequences at Mukdahan station. (SRI6_May means based on 6-month precipitation from December to May; SRI3_May means based on 3-month precipitation from March to May).

The dry season SRI sequence also shows an upward trend at Stung Treng station (Figure 5.3-15). After 1995, it is characterized by alternation of high and low flow in the dry season. Among them, in the late 1980s and early 1990s, the SRI value was as small as -1.7, which indicates severe hydrological drought.

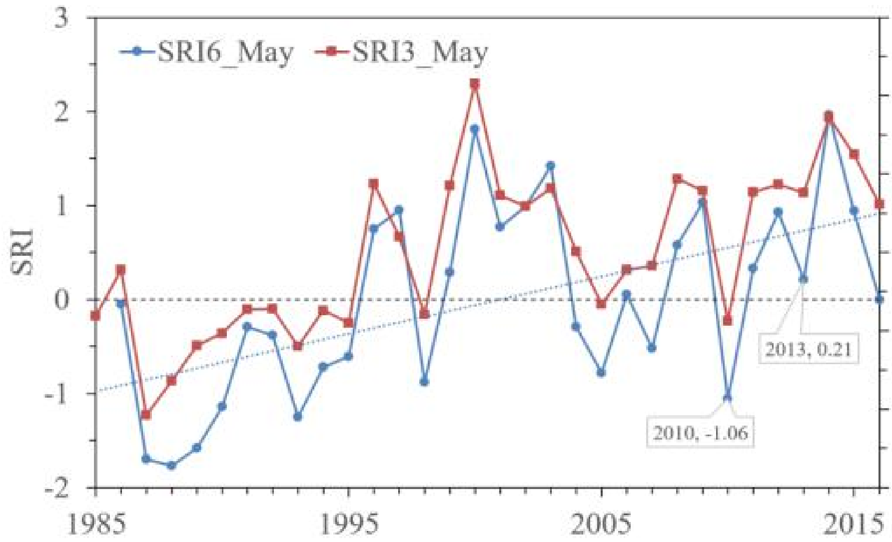


Figure 5.3-15 | SRI sequences at Stung Treng station. (SRI6_May means based on 6-month precipitation from December to May; SRI3_May means based on 3-month precipitation from March to May).

The SRI results at hydrological stations along Mekong mainstream during the dry season of 2009-2010 and 2012-2013 are shown in Table 5.3-4. Although the dry season rainfall in 2012-2013 and 2009-2010 were relatively low and meteorological drought occurred, it can be seen from the table that no hydrological drought occurred at the hydrological stations of Mekong mainstream in 2012-2013.

Table 5.3-4 | SRI6 results at hydrological stations along Mekong mainstream during the two drought event (December to May).

	Chiang Saen	Luang Prabang	Nong Khai	Nakhon Phanom	Mukdahan	Pakse	Stung Treng
2009-2010	-0.59	-0.88	-0.99	-1.16	-0.54	-1.03	-1.06
2012-2013	0.88	0.68	0.30	0.75	1.13	0.91	0.21

(2) Hydrological Frequency Analysis

According to the hydrological frequency analysis, the hydrological drought in dry season of 2012-2013 is less severe than that of 2009-2010. Especially for Chiang Saen station at the upper stream, the severity of drought (frequency) of the minimum daily average flow and minimum monthly average flow during the dry season of 2009-2010 reaches 1 in 12 years, while that of 2012-2013 is around the normal state.

Table 5.3-5 | The recurrence period of the minimum daily average discharge at the main stations along Mekong mainstream during the two typical droughts Unit: year.

Drought	Chiang Saen	Luang Prabang	Nong Khai	Nakhon Phanom	Mukdahan
2009-2010	12.7	3.8	9.1	7.7	2.9
2012-2013	2.0	1.5	3.1	1.5	1.1

Table 5.3-6 | The recurrence period of the minimum monthly average discharge at the main stations along Mekong mainstream during the two typical droughts Unit: year.

Drought	Chiang Saen	Luang Prabang	Nong Khai	Nakhon Phanom	Mukdahan
2009-2010	12.8	4.3	10.5	7.9	2.7
2012-2013	1.3	1.2	1.7	1.3	1.2

Table 5.3-7 | The recurrence period of the minimum 3-month average discharge at the main stations along Mekong mainstream during the two typical droughts Unit: year.

Drought	Chiang Saen	Luang Prabang	Nong Khai	Nakhon Phanom	Mukdahan
2009-2010	3.6	3.0	4.8	5.8	2.2
2012-2013	1.2	1.2	1.4	1.2	1.1

5.3.5 Comparison of Meteorological and Hydrological drought

When the time scale reaches 6-month and above, the SPI could be applied for hydrological drought analysis. So we based on the results of SPI6 and SRI6 to investigate the relations between meteorological drought and hydrological drought on the drainage areas of the hydrological stations along the Mekong mainstream.

SPI6 and SRI 6 (December-May) at the main hydrological stations along Mekong mainstream in the dry season of 2009-2010 and 2012-2013 are shown in Figure 5.3-16 and Figure 5.3-17. From the figures, SPI6 and SRI6 in 2009-2010 showed good consistency. Most of the meteorological and hydrological droughts in the study areas were light or moderate. While SPI6 and SRI6 in 2012-2013 showed significant differences. The meteorological drought was mild or moderate, but the hydrological conditions were normal or relatively abundant. This indicates that in the dry season of 2012-2013, the actual inflow from the upper reaches is larger than that could be generated by the precipitation, which may be due to water supplement from the Lancang hydropower cascade to the Mekong River.

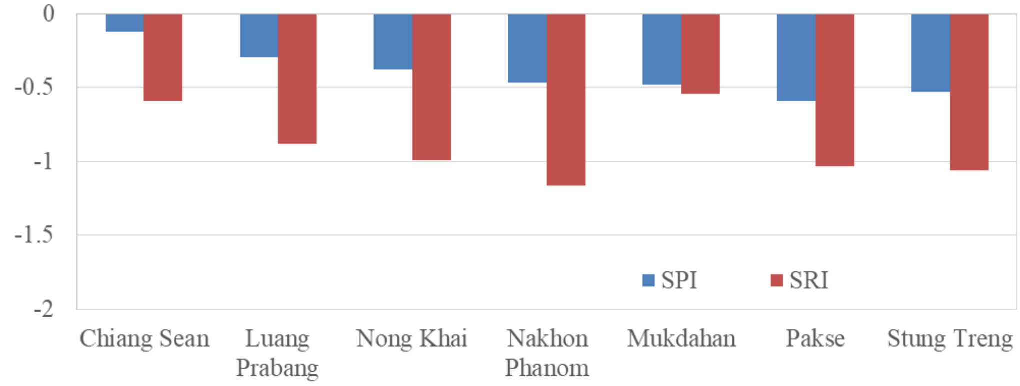


Figure 5.3-16 | SPI6 and SRI6 (December to May) at hydrological stations along the Mekong mainstream for the dry season of 2009-2010.

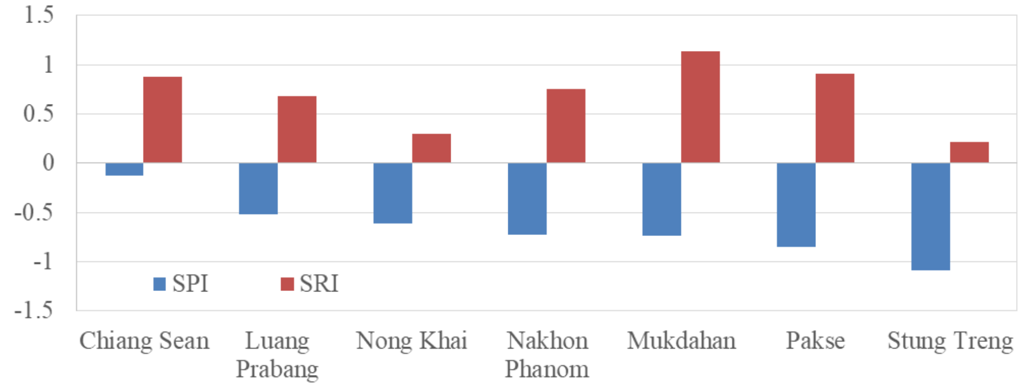


Figure 5.3-17 | SPI6 and SRI6 (December to May) at hydrological stations along the Mekong mainstream for the dry season of 2012-2013.

5.4 Effect of Water Supplement of Lancang Hydropower Cascade on the Lower Reaches

5.4.1 Impact on the Mekong Mainstream Flow

The monthly average flow of the Lancang-Mekong River main stream hydrological stations in the dry season of 2009-2010 and 2012-2013 is shown in Figure 5.4-1 and Figure 5.4-2. From Fig. 4.1-2, it can be seen that the flow of Chiang Saen station is close to that of Nong Khai station, indicating that the contribution rate of Chiang Saen inflow to Chiang Saen-Nong Khai stretch is high, and the runoff yield in this region is very limited in the dry season of 2012-2013.

It can be seen from the monthly discharge of the Lancang-Mekong main stream hydrological stations (Figure 5.4-3) that, due to the meteorological drought in the Lancang-Mekong River Basin in 2009-2010, the flow along the Lancang-Mekong River is lower than the average. Although meteorological drought also occurred in the dry season of 2012-2013, the monthly discharge of Jinghong station is higher than that of 2009-2010 and the multi-year average, and the monthly discharge of Chiang Saen station in the dry season of 2012-2013 was higher than the multi-year average, which should be due to the water supplement from Lancang hydropower cascade.

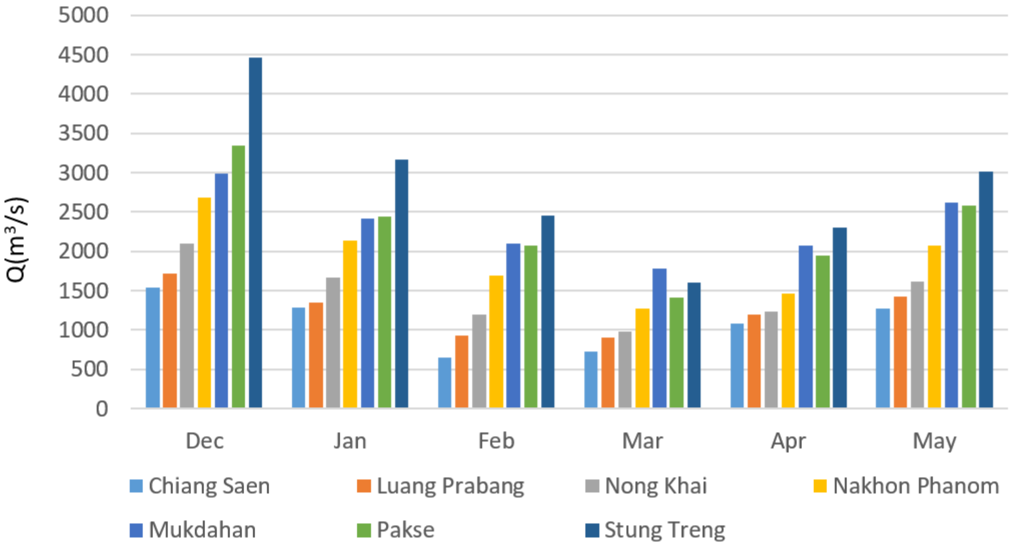


Figure 5.4-1 | General pattern of monthly average discharge along the Mekong mainstream for the dry season of 2009-2010.

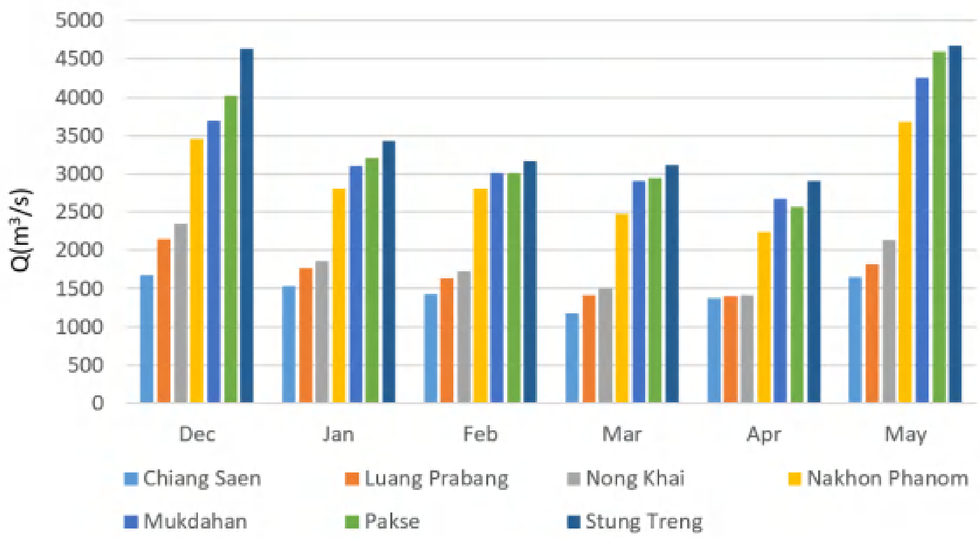


Figure 5.4-2 | General pattern of monthly average discharge along the Mekong mainstream for the dry season of 2012-2013.

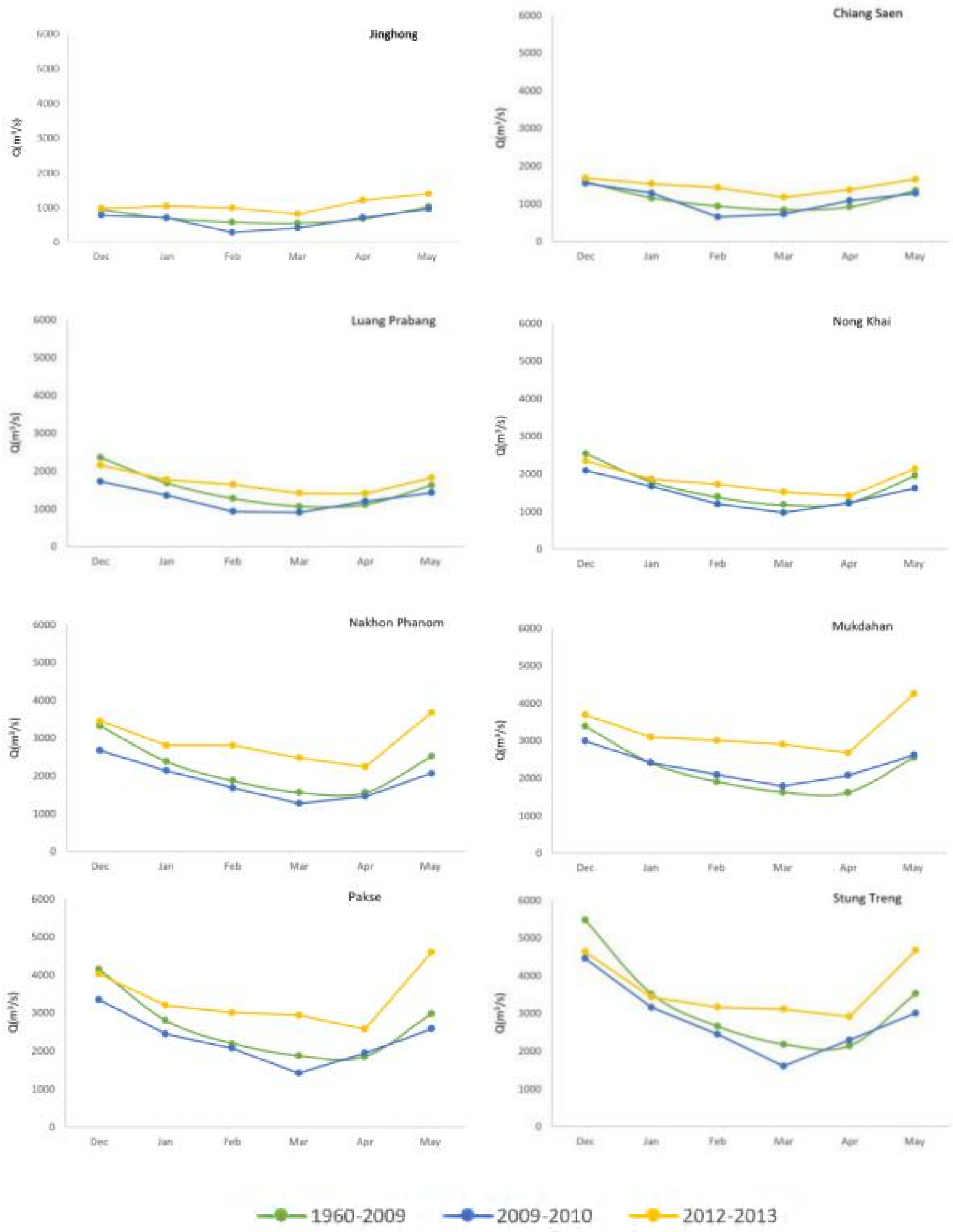


Figure 5.4-3 | Comparison of monthly average discharge along the Lancang-Mekong mainstream for the dry season of 1960-2009, 2009-2010 and 2012-2013.

5.4.2 Impact on the Mekong Mainstream Water Level

Table 5.4-1 shows the monthly average water level along the Lancang-Mekong mainstream for the dry season of 1960-2009, and the deviation with that of 2009-2010 and 2012-2013. It can be seen from the table that in the dry season of 2009-2010, the water level of most stations is lower than the historical average level, and the water level of Chiang Saen station is equal to or slightly higher than the historical average level. In the dry season of 2012-2013, the water level of most stations is higher than the historical average level, the water level of Jinghong station and Chiang Saen station is 0.30-0.71 and 0.46-1.11 meter higher than the historical average level respectively during January and May, 2013.

Table 5.4-1 | Deviation of monthly average water levels in the dry season of 2009-2010, 2012-2013, and 1960-2009.

Station	December	January	February	March	April	May
Average water level in 1960-2009*(m, local datum)						
Jinghong	535.69	535.20	534.96	534.89	535.11	535.70
Chiang Saen	2.22	1.65	1.28	1.10	1.24	1.90
Luang Prabang	5.63	4.57	3.82	3.37	3.45	4.37
Nong Khai	3.05	2.17	1.60	1.26	1.34	2.23
Nakhon Phanom	2.35	1.59	1.15	0.91	0.93	1.75
Mukdahan	2.50	1.86	1.51	1.31	1.29	1.9
Pakse	1.93	1.26	0.94	0.75	0.74	1.31
Stung Treng	3.14	2.58	2.27	2.07	2.03	2.52
Deviation of average water level between 1960-2009 and 2009-2010 (m)						
Jinghong	-0.54	-0.06	-0.78	-0.35	0.05	-0.17
Chiang Saen	0.30	0.55	0.01	0.33	0.71	0.29
Luang Prabang	-1.08	-0.71	-0.90	-0.50	0.09	-0.38
Nong Khai	-0.69	-0.39	-0.58	-0.63	-0.25	-0.52
Nakhon Phanom	-0.77	-0.45	-0.42	-0.58	-0.40	-0.67
Mukdahan	-0.67	-0.43	-0.32	-0.37	-0.11	-0.33
Pakse	-0.54	-0.32	-0.21	-0.40	-0.07	-0.30
Stung Treng	-0.21	-0.03	0.05	-0.04	0.24	-0.02
Deviation of average water level between 1960-2009 and 2012-2013 (m)						
Jinghong	-0.20	0.36	0.54	0.30	0.71	0.38
Chiang Saen	0.46	0.86	1.11	0.95	1.06	0.74
Luang Prabang	-0.37	0.06	0.58	0.59	0.49	0.35
Nong Khai	-0.38	-0.12	0.26	0.27	0.03	0.19
Nakhon Phanom	-0.22	0.09	0.52	0.51	0.29	0.54
Mukdahan	-0.24	0.04	0.33	0.46	0.32	0.69
Pakse	-0.22	0.06	0.29	0.45	0.26	0.65
Stung Treng	-0.17	0.05	0.28	0.46	0.44	0.46

**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.*

5.4.3 Impact on the Mekong Mainstream Water Volume

Based on monthly average flow data of 1960-2009, 2009-2010 and 2012-2013, the dry season (December to May) water volume and its contribution rate to the annual water volume was calculated at the 8 stations along Lancang-Mekong mainstream. The results show that there was an increase of 5.08 billion m3 of the dry season water volume at Jinghong station in 2012-2013 compared with the 1960-2009 average, increasing from multi-year average 11.82 billion m3 to 16.90 billion m3. And it was also 6.7 billion m3 more than that of 2009-2010. For the dry season water volume at Chiang Saen station in 2012-2013, it was increased from multi-year average 17.79 billion m3 to 23.15 billion m3, with an increase of 5.36 billion m3, and it was also 5.89 billion m3 more than that of 2009-2010. Though meteorological drought happened in the Lancang River Basin in 2012-2013, the dry season water volume at stations along Mekong mainstream was higher than the multi-year average due to the water supplement from Lancang hydropower cascade, as shown in Table 5.4-2.

Table 5.4-2 | Volume in the dry season of 1960-2009, 2009-2010 and 2012-2013 along the Lancang-Mekong mainstream.

Station	Volume of the dry season (billion m^3)			Deviation of volume between (billion m^3)	
	1960-2009* (% annual volume)	2009-2010 (% annual volume)	2012-2013 (% annual volume)	2012-2013 and 1960-2009	2012-2013 and 2009-2010
Jinghong	11.82 (21%)	10.20(-)	16.90(-)	5.08(-)	6.70(-)
Chiang Saen	17.79 (21%)	17.27(24%)	23.15(33%)	5.36(12%)	5.89(9%)
Luang Prabang	23.99 (19%)	19.83(21%)	26.74(25%)	2.75(6%)	6.91(4%)
Nong Khai	26.57 (18%)	23.12(18%)	28.87(22%)	2.30(4%)	5.75(4%)
Nakhon Phanom	34.85 (15%)	29.69(14%)	45.87(19%)	11.02(4%)	16.17(5%)
Mukdahan	35.59 (14%)	36.71(15%)	51.56(19%)	15.97(5%)	14.85(4%)
Pakse	41.74 (13%)	36.26(13%)	53.49(17%)	11.75(4%)	17.23(14%)
Stung Treng	51.41 (13%)	44.65(15%)	57.66(14%)	6.25(1%)	13.02(-1%)

** 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.*

From Table 5.4-3, Figure 5.4-4 and Figure 5.4-5, it could be seen that the dry season water volume along Lancang-Mekong mainstream is more than the multi-year average, and the contribution of volume in dry season at Jinghong station to that at stations along Mekong mainstream is higher than multi-year average.

Table 5.4-3 | Contribution of volume in the dry season of 1960-2009, 2009-2010 and 2012-2013 at Jinghong to that at stations along the Mekong mainstream.

Station	Volume of the dry season (billion m^3)			Deviation of volume between (billion m^3)		
	1960-2009 (% Jinghong)	2009-2010 (% Jinghong)	2012-2013 (% Jinghong)	2009-2010 and 1960-2009	2012-2013 and 1960-2009	2012-2013 and 2009-2010
Jinghong	11.82 (100%)	10.20 (100%)	16.90 (100%)	-1.62	5.08	6.70
Chiang Saen	17.79 (66%)	17.27 (59%)	23.15 (73%)	-0.52	5.36	5.89
Luang Prabang	23.99 (49%)	19.83 (51%)	26.74 (63%)	-4.16	2.75	6.91
Nong Khai	26.57 (44%)	23.12 (44%)	28.87 (58%)	-3.45	2.30	5.75
Nakhon Phanom	34.85 (34%)	29.69 (34%)	45.87 (37%)	-5.16	11.02	16.17
Mukdahan	35.59 (33%)	36.71 (28%)	51.56 (33%)	1.12	15.97	14.85
Pakse	41.74 (28%)	36.26 (28%)	53.49 (32%)	-5.48	11.75	17.23

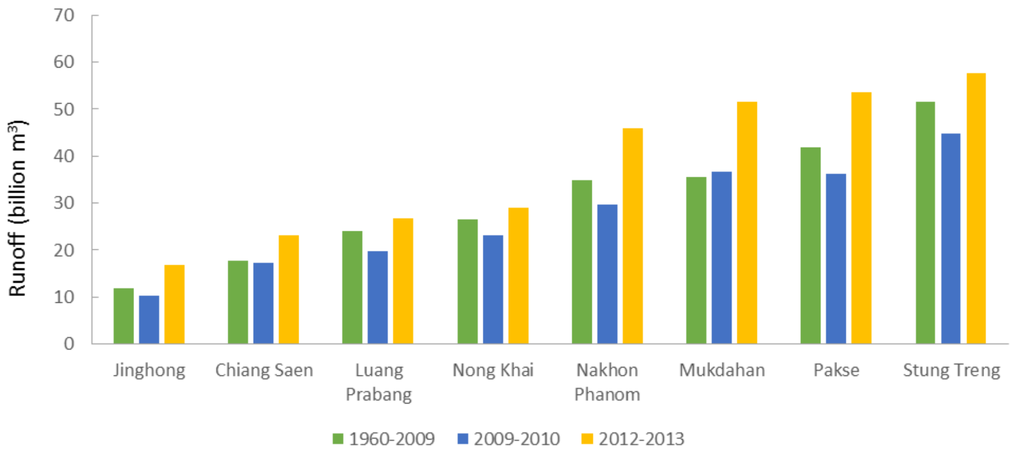


Figure 5.4-4 | Accumulated volume in the dry season at stations along the Lancang-Mekong mainstream.

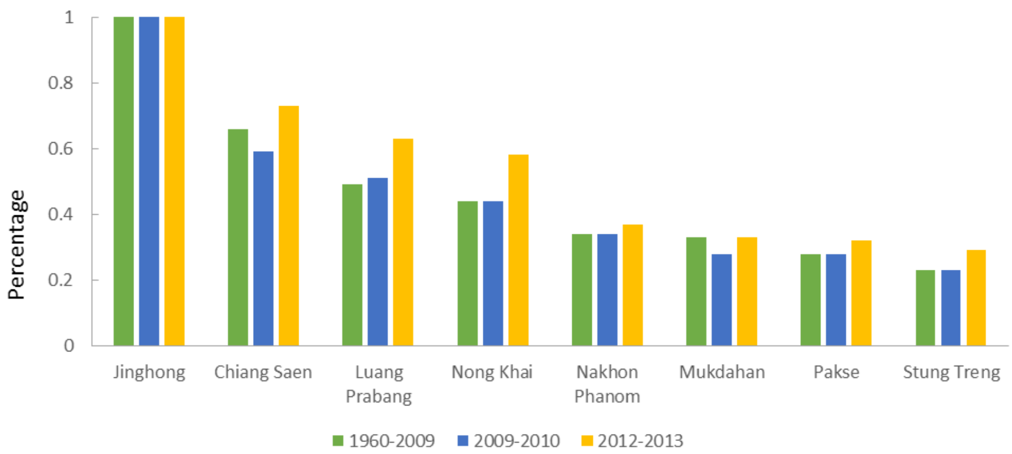


Figure 5.4-5 | Contribution of volume in the dry season at Jinghong to that at stations along the Mekong mainstream.

5.5 Discussion

(1) The time needed from rainfall to runoff generation varies according to the basin, and it takes about 17 days for flow to propagate from Jinghong to Stung Treng station. Therefore, hydrological drought should be lagged behind meteorological drought. SPI and SRI in this study are monthly and above scales, which could not reflect this lag effect. Considering that the propagation time of flow in the basin is less than one month, it is assumed that the influence on SPI and SRI results at three-month and six-month scales is small.

(2) The discharge data at hydrological stations along the Mekong mainstream was provided by the MRCS, which was calculated based on rating curves. According to our knowledge, the rating curves adopted by Chiang Saen station in different historical periods are different. The consequent errors may affect the SRI results. This effect has not been discussed in this study.

6 Analysis of extreme drought of 2015-2016

The effect of the emergency water supplement from China for the drought of 2015-2016 was evaluated since 2016 under the joint research with China on ***Joint Observation and Evaluation of the Emergency Water Supplement from China to the Mekong River (MRC, 2016)***. The approach was by analyzing daily water level, discharge, and long-term average of dry season flow conditions of 1960-2009 and 2010-2015. The evaluation focused on the generic analyses of the drought in the Lancang-Mekong Basin and influential hydrological factors of Mekong water flow/volume of the emergency water supplement.

The major contexts of this chapter are the findings extracted from the report of that research which are manipulated with some additional information as shown in the following sections.

6.1 Background

The meteorological and agricultural drought conditions in 2015-2016 over the Mekong Basin have worsened and triggered China to implement its emergency water supplement from its cascades dams in the Lancang River to the Mekong River by increasing the water discharge from Yunnan's Jinghong Reservoir. China decided to implement its emergency water supplement in a 'three-phase plan': (1) from 9 March to 10 April 2016, with an average daily discharge of no less than 2,000 m^3/s; (2) from 11 April to 20 April 2016 with the discharge of no less than 1,200 m^3/s; and (3) from 21 April to 31 May 2016 with the discharge of no less than 1,500 m^3/s. The Mekong River Commission acknowledges this action by China, in which China has also stated that it implemented the water supplement at a challenging time, especially within the context where China itself was also suffering from drought, which has affected its household water supply and agricultural production.

The China's Ministry of Water Resources and Mekong River Commission Secretariat then co-organised experts from both sides to conduct a Joint Observation and Evaluation of the Emergency Water Supplement from China and its effect of easing the drought situation in the Mekong Basin.

Due to time constraint and resources limitation, only water level and discharge of the key hydrological stations along the Lancang-Mekong mainstream before and after the emergency water supplement are analysed to evaluate the effect of the emergency water supplement. The evaluation covers the generic analysis of the drought in the Lancang-Mekong Basin, analysis of influential factor contribution to flows of the Mekong River, hydrological influence analysis and descriptive benefit analysis of the emergency water supplement.

The scope of the Joint Observation and Evaluation covers: (1) Temporal Scope – dry season[13] of 2016, which runs from 1 December 2015 to 31 May 2016 and especially during the emergency

[13] For the purpose of the Joint Observation and Evaluation, the dry season is considered from 1 December to 31 May.

water supplement period from 15 March to 15 May 2016; and (2) Spatial Scope – from Jinghong hydrological station on the Lancang River to the Mekong Delta.

The analyses cover (1) Cause of the drought in the Lancang-Mekong Basin considering temperature, rainfall, flows, soil moisture and water stress; (2) Overall influence of Lancang cascade reservoirs operation on dry season volume of the Mekong River; (3) Hydrological influence of the emergency water supplement in 2016 on water level, discharge and volume of the Mekong mainstream; (4) Net contribution of the water supplement to discharge of the Mekong River; (5) Variation of water level and discharge of the Mekong mainstream during the water supplement; (6) Flow propagation along the mainstream; and (7) Salinity variation in the Mekong Delta during the period of the emergency water supplement.

Location of the hydrological stations on the Lancang- Mekong mainstream is illustrated in **Figure 6.2-1**.

6.2 Implementation of the emergency water supplement from the Lancang River

China decided to implement a 'three-phase plan' of emergency water supplement to the Mekong River by notifying the MRCS and its Member Countries on 15 March 2016. The plan covers (1) from 9 March to 10 April 2016, with an average daily discharge of no less than 2,000 m^3/s; (2) from 11 April to 20 April 2016 with the discharge of no less than 1,200 m^3/s; and (3) from 21 April to 31 May 2016 with the discharge of no less than 1,500 m^3/s.

On 15 March 2016, the discharge from Jinghong Reservoir increased to 2,190 m^3/s, marking officially the beginning of the emergency water supplement from cascade reservoirs of the Lancang River. From 9 March to 10 April 2016, the volume at Jinghong accumulated to 6.10 billion m^3, with daily average discharge of 2,170 m^3/s, which was increased by 1,570 m^3/s comparing with the discharge without dam regulation.

Figure 6.2-1 | Location of hydrological stations along the Lancang-Mekong River.

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

To respond to the need of security-related activities for the Water Splashing Festival of Dai people[149] in Xishuangbanna from 11 April to 20 April 2016, the discharge of Jinghong Reservoir was regulated to 1,200 m^3/s. From 00:00 on 11 April 2016, the discharge of Jinghong Reservoir was regulated in a smooth way and decreased gradually from 2,100 m^3/s to 1,200 m^3/s, guaranteeing safe navigation in the downstream and meeting the need of related activities during the Water Splashing Festival. The discharge from Jinghong Reservoir was then reached approximately 1,200 m^3/s at 05:00 on 11 April 2016. From 11 April to 20 April 2016, the volume at Jinghong accumulated to 1.07 billion m^3, with daily average discharge of 1,234 m^3/s, which was increased by 363 m^3/s comparing to the discharge without dam regulation.

The discharge of Jinghong Reservoir was then controlled to no less than 1,500 m^3/s from 21 April to 31 May 2016. The accumulated volume of this period was 5.48 billion m^3.

From 9 March to 31 May 2016, the total released volume at Jinghong was found to be 12.65 billion m^3.

6.3 Analysis of cause of the drought in the Lancang- Mekong Basin

Cause of the drought in the Lancang-Mekong Basin was assessed by considering status of the El Niño 2015-2016 and monitoring data of temperature, rainfall, flows, soil moisture, and water stress.

6.3.1 Rainfall and inflow discharge to the Lancang Basin

From November 2015 to April 2016, the average rainfall in the upstream catchment of Jinghong was 166.9 mm by statistical analysis according to the measured rainfall in the Lancang Basin, which was decreased by 19% comparing with an average rainfall of 206.4 mm of the same period.

Moreover, inflow discharge to Xiaowan Reservoir and Nuozhadu Reservoir from November 2015 to March 2016 was calculated and then compared to the long term average values, the results are presented in **Table 6.3-1**. The inflow discharges to Xiaowan Reservoir and Nuozhadu Reservoir were found to be reduced by 14%-38% and 10%-38% respectively, comparing to the long term average values of the same period.

[14] The Dai people belong to an ethic group that is spread widely in the southwest of China, but is concentrated in the southern part of Yunnan Province. Jinghong is the capital city of Xishuangbanna Dai Autonomous Prefecture. The biggest festival of the Dai people is the New Year celebrations (or Water Splashing Festival) held during the sixth month of the Dai calendar, usually falling in the middle of April. The New Year celebrations last for 3 days. Due to historical reasons, the New Year for the Dai people of Xishuangbanna is from April 13 to 15. During the festival, visitors can experience exciting water splashing activities, and other activities, such as cock fighting, dragon boat racing, and water lantern floating (China Highlights: http://www.chinahighlights.com/video/the-water-splashing- festival.htm, accessed on 09 June 2016).

In short, from the aspects of measured rainfall and inflow discharge to Xiaowan Reservoir and Nuozhadu Reservoir, it generally suggests that the Langcang Basin was experienced shortage of inflows from November 2015 to March 2016.

Table 6.3-1 | Conditions of inflow discharge to Xiaowan Reservoir and Nuozhadu Reservoir from November 2015 to March 2016.

Inflow discharge (m^3/s)	November	December	January	February	March
Xiaowan Reservoir					
Inflow to Xiaowan in 2016	537	409	324	326	351
Inflow to Xiaowan without upstream dams in 2016	544	404	321	321	360
Long term average inflow of 1960-2006	875	553	420	380	418
Ratio of reduction to long term average	-38%	-27%	-24%	-16%	-14%
Nuozhadu Reservoir					
Inflow discharge to Nuozhadu in 2016	1,110	1,240	1,230	731	901
Inflow to Nuozhadu without upstream dams in 2016	933	692	535	501	459
Long term average inflow discharge of 1960-2006	1,500	915	668	559	536
Ratio of reduction to long term average	-38%	-24%	-20%	-10%	-14%

6.3.2 Hydrological Condition at the end of Wet Season 2015

The flow conditions in the Mekong at monitoring sites from Jinghong down to Kratie as shown in Figure 6.3-1 over the entire flood period in general were significantly below their long-term average level magnitudes. There was only one obvious storm event in August that caused the Mekong levels in the upper and middle reaches rose up above its average for 1-2 weeks. The water levels in July were lowest since ever recorded from 1960 with an exemption when the Mekong River entering Cambodia at Stung Treng as the flow was generally dominated by runoff over the middle stretch. At the end of the flood season, water levels in Mekong river were still critically low. This low river flow condition was a factor to promote drought during the dry period of 2015-2016.

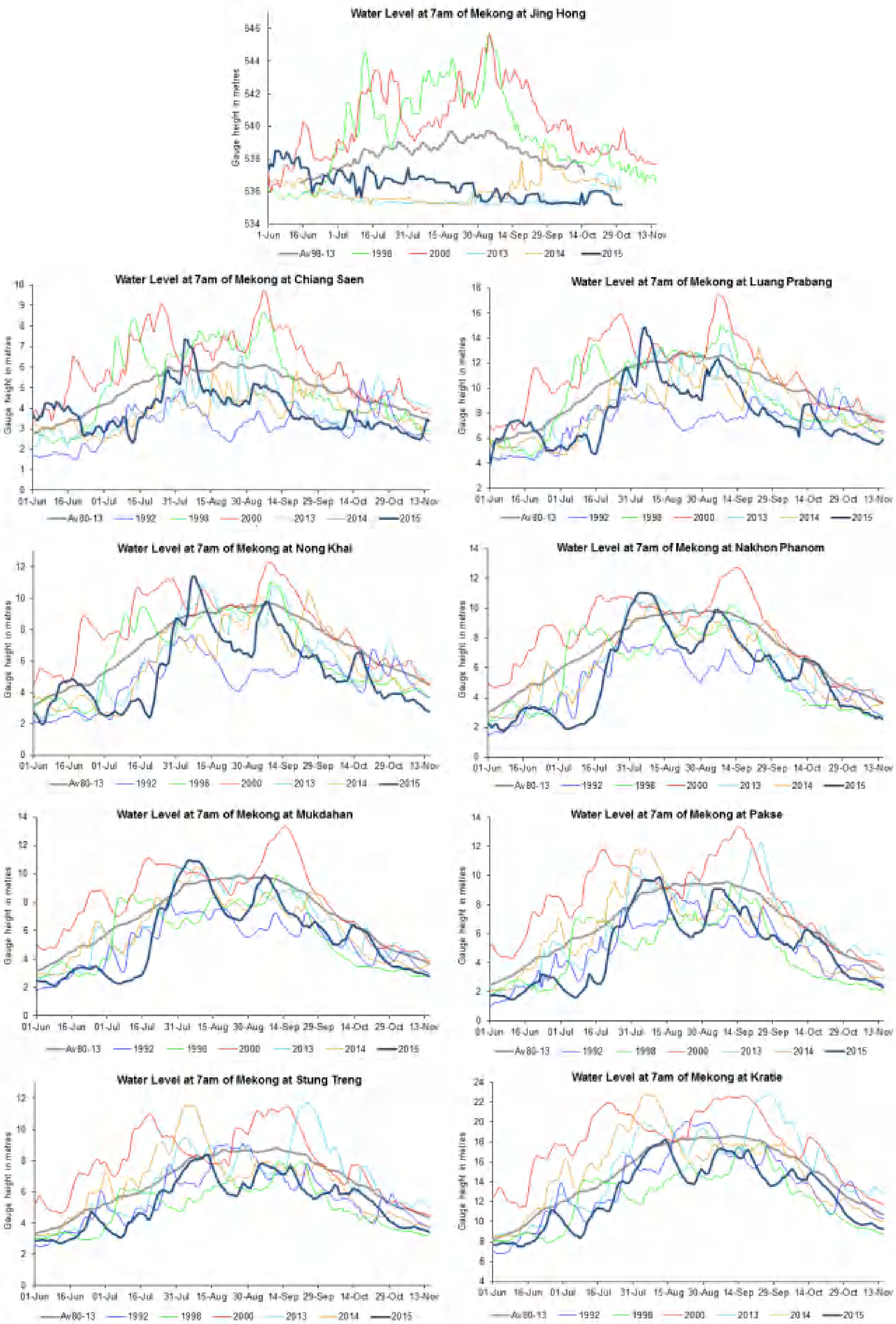


Figure 6.3-1 | The 2015 daily water level hydrographs in flood season from 1 June to 31 October observed at selected sites compared to the long-term averages and other selected flood seasons

6.3.3 *Drought in the Mekong Basin*

The drought phenomenon is usually grouped into four types[15].

- Meteorological or climatological drought, which focuses on the degree of 'dryness' in terms of an accumulated rainfall deficit.
- Agricultural drought, which expresses the rainfall shortfall primarily in terms of its impact upon crop production through insufficient soil moisture. It generally applies to rainfed agriculture, though irrigated crops can be affected when the water resources themselves become restricted or too expensive.
- Hydrological drought refers to shortages in both surface water and groundwater. This can take the form of critically low river flow, drawn-down reservoir storage and deeper groundwater levels, which make pumped abstraction too expensive or mechanically impossible.
- Socio-economic drought associates the supply and demand consequences for economic goods. Energy outputs from hydropower schemes can be curtailed due to low stream flow and low levels of reservoir storage. There are industrial, agricultural, environmental and social consequences from any curtailment of water supply and water use during droughts.

(1) El Niño 2015-2016 and El Niño 1997-1998

The El Niño 2015-2016 is strong and appears likely to equal the event of 1997-1998, the strongest El Niño on record, according to the World Meteorological Organization. The super El Niño of 2015-2016 was highly on alert. Data from NASA[16] reveals side-by-side comparisons of Pacific Ocean sea surface height anomalies[17] of what was happening to the Pacific Ocean El Niño signal with the famous El Niño 1997-1998 (which peaked in November 1997). The El Niño 2015- 2016, which peaked in January 2016, was longer lasting than the 1997-1998 episode and was larger in area. The El Niño of 2015-2016 was similar to the El Niño of 1997-1998, but not an exact repeat. Each El Niño episode had a unique timing and variations in impacts. It should be noted that the El Niño of 2015-2016 was a continuing El Niño that first appeared in 2014-2015[18]. Comparing 2015-

[15] Wilhite, D. A. & Glantz, M. H., 1985. Understanding the drought phenomenon: the role of definitions, Water International, 10(3), pp. 111–120. World Meteorological Organization. December 2009. Experts agree on a universal drought index to cope with climate risks. Press release No. 872

[16] Jet Propulsion Laboratory, United States National Aeronautics and Space Administration (NASA):https://sealevel.jpl.nasa.gov/science/elninopdo/latestdata/, accessed on 7 June 2016.

[17] Height of the sea surface is caused by both gravity (which doesn't change much over 100's of years), and the active (always changing) ocean circulation. The normal slow, regular circulation (ocean current) patterns of sea-surface height move up and down (warming and cooling and wind forcing) with the normal progression of the seasons: winter to spring to summer to fall. The differences between what is normal for different times and regions are called anomalies or residuals. The year-to-year and, even, decade-to-decade changes in the ocean that indicate climate events such as the El Niño, La Niña and Pacific Decadal Oscillation are dramatically visualized by these data. Sea surface height is the most modern and powerful tool for taking the 'pulse' of the global oceans (NASA: https://sealevel.jpl.nasa.gov/science/elninopdo/latestdata/, accessed on 7 June 2016).

[18] United States National Aeronautics and Space Administration (NASA), http://www.nasa.gov/feature/goddard/nasa-studying-2015-el-nino-event-as-never-before, accessed on 8 June 2016.

2016 conditions with 1997-1998, a large area of the northeastern tropical Pacific (north of the equator) still contained a large area of positive heat content (warmer than normal).

(2) Temperature

The average on temperature departure from the normal average shows that during mid-January between 11 and 20 January 2016, the Mekong Basin received a high temperature starting from middle part of the basin towards southern part of the region between 3-5 °C above the normal average[19]. However, the condition lasted for only around two weeks. Northeast Thailand, Lao PDR and North Viet Nam, nevertheless, experienced lower temperature than the average in February 2016. The temperature started rising up again in early March across the region and intensifying in some areas with severe condition in April 2016. It is considered that the region received highest temperature at national records.

(3) Rainfall

Satellite rainfall from the Tropical Rainfall Measuring Mission (TRMM) presented in **Figure 6.3-2** reveals rainfall conditions over the Mekong Basin from January to April 2016. The observation shows the northern part of Lao PDR received small amount of rainfall in January 2016. There was almost no rain over the Mekong Basin in February and March 2016. In April, most areas of the Mekong Basin, except for the Mekong Delta, received some small amount of rainfall between 20 to 200 mm. Lao PDR received the most accumulated rainfall between 50-200 mm in April, especially in the north and middle parts of the country. Point rainfall at the ground was also observed at all hydrological stations (**Figure 6.2-1**). Rainfall amount for March-May 2016 was mainly concentrated in late April and early May as recorded at Luang Prabang, Chiang Khan and Nakhon Phanom. It is shown that only small amount of rainfall was observed over the Mekong Basin.

[19] Average daily air temperature is calculated for each grid cell by averaging the twenty-four 1-hourly air temperatures. The dekadal average air temperature is then estimated by averaging the ten daily air temperatures for each grid cell. The temperature data is derived from satellite weather data from the Air Force Weather Agency (AFWA).

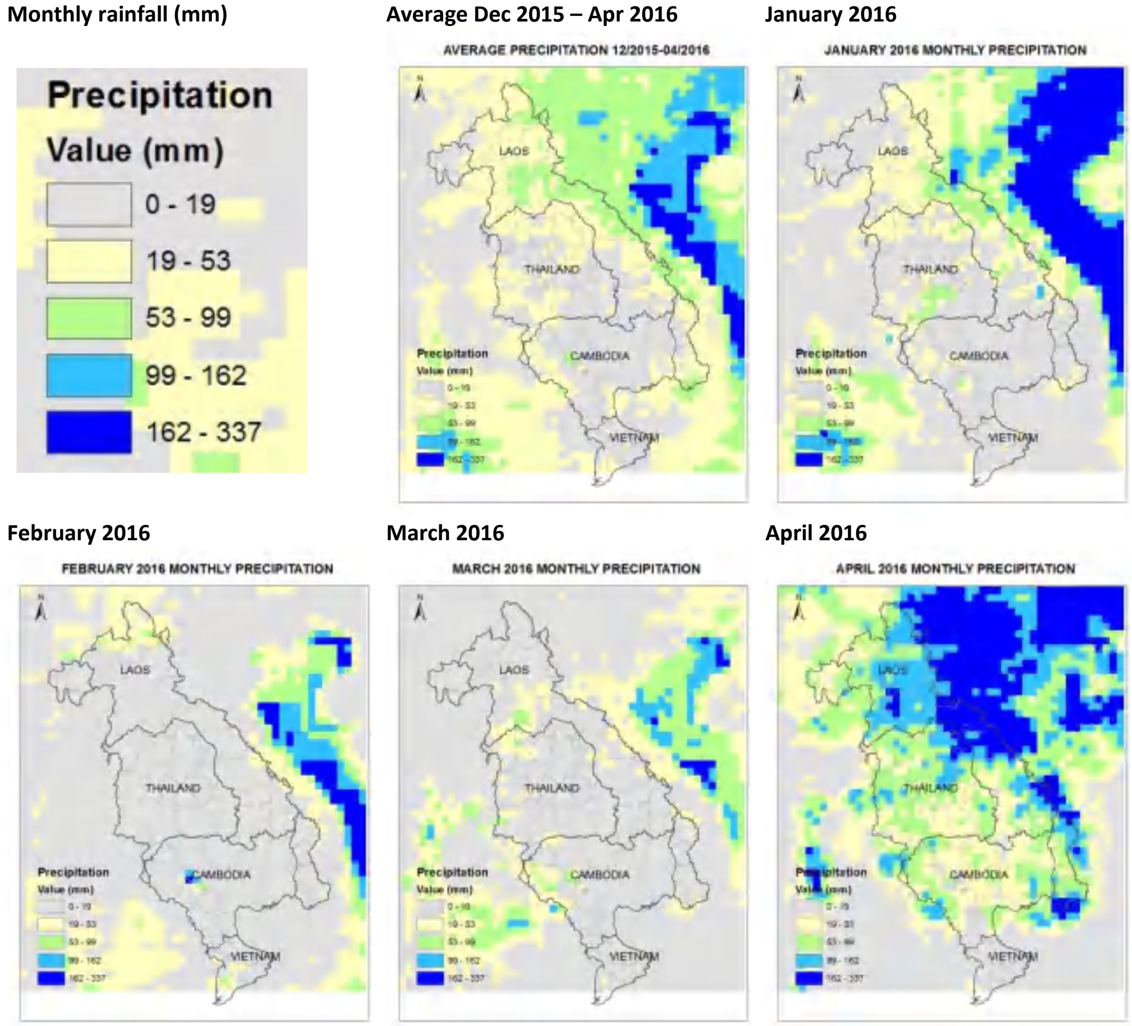


Figure 6.3-2 | Monthly rainfall over the Mekong Basin from the Tropical Rainfall Measuring Mission (TRMM) for January-April 2016.

(4) Subsurface soil moisture

Subsurface soil moisture[20] levels are best used to monitor an established crop. The subsurface soil moisture is assumed to hold 0-400 mm/m of water depending on the soil's water-holding capacity (based on soil texture and soil depth).

Subsurface soil moisture started getting worse in March 2016 in Thailand, Cambodia and Mekong Delta (**Figure 6.3-3**). The moisture content remained less than 25 mm making unfavorable

[20] The soil moisture model assumes rainfall enters the two soil layers by first filling the surface soil layer and then filling the lower soil layer. Moisture is extracted from the two soil layers by evapotranspiration, whereby water is first depleted from the top layer and then extracted from the subsurface layer. When the water-holding capacity of both soil layers is reached, excess rainfall is lost from the model and treated as runoff or deep percolation. Subsurface soil moisture levels ranging from: >100 mm indicates an abundance or at least favourable amount of moisture in the subsoil; <100 mm indicates the subsurface soil moisture storage is short but can still support a well- established crop; and <25 mm has very little subsurface soil moisture and the crop could be severely stressed and reduce yields, especially if it occurs when the top layer has little or no significant soil moisture and the crop is at a critical stage of growth.

condition for the crops. The dry condition intensified in the following months of April. Only some small part of the east Thailand received some moisture in fourth week of April as the rain pours down (**Figure 6.3-2 |**). Western part of Lao PDR had a better soil moisture condition throughout the dry season 2016.

(5) Normalised Difference Water Index

The Normalized Difference Water Index[21] (NDWI) or water stress for agriculture is a satellite-derived index from the Near-Infrared (NIR) and Short Wave Infrared (SWIR) channels. Map of the NDWI depicted in **Figure 6.3-4** shows that, starting from fourth week of January 2016, the water stress value was already at moderate level in northeast Thailand and around floodplain of the Tonle Sap Lake of Cambodia. The condition became worse in February to end of April, which would damage a large area of agricultural production in northeast Thailand and Cambodia. The water stress conditions became less serious towards the end of April in these two countries, thanks to rainfall over the Mekong Basin. However, it looks relatively good for Lao PDR and Mekong Delta during January-April 2016.

[21] The Normalized Difference Water Index (NDWI) is a satellite-derived index from the Near Infrared (NIR) and Short Wave Infrared (SWIR) channels. The SWIR reflectance reflects changes in both the vegetation water content and the spongy mesophyll structure in vegetation canopies, while the NIR reflectance is affected by leaf internal structure and leaf dry matter content but not by water content. The combination of the NIR and SWIR removes variations induced by leaf internal structure and leaf dry matter content, improving the accuracy in retrieving the vegetation water content. The amount of water available in the internal leaf structure largely controls the spectral reflectance in the SWIR interval of the electromagnetic spectrum. The SWIR reflectance is therefore negatively related to leaf water content.

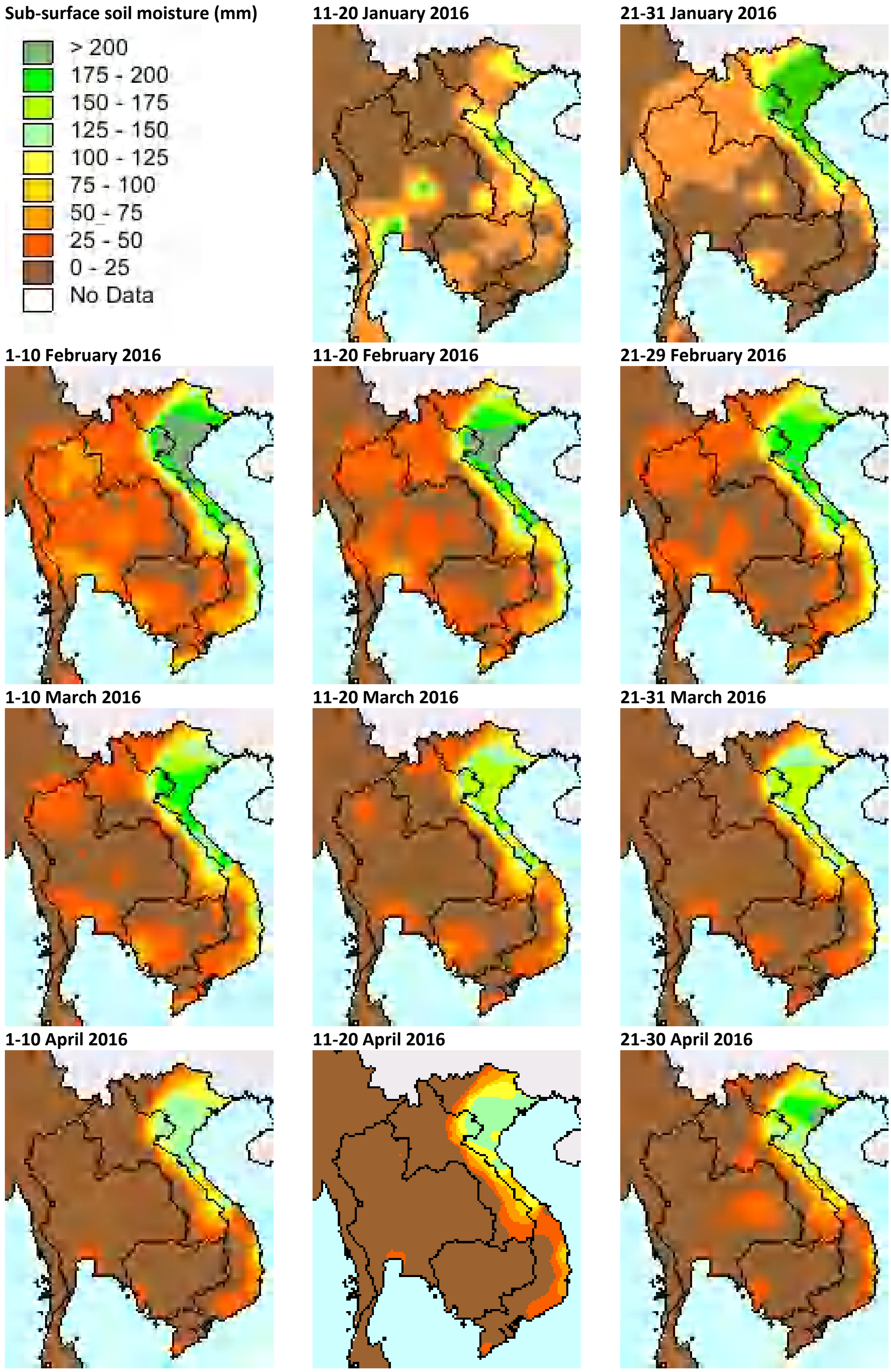


Figure 6.3-3 | Subsurface soil moisture monitoring from the World Meteorological Organisation (WMO) for January-April 2016.

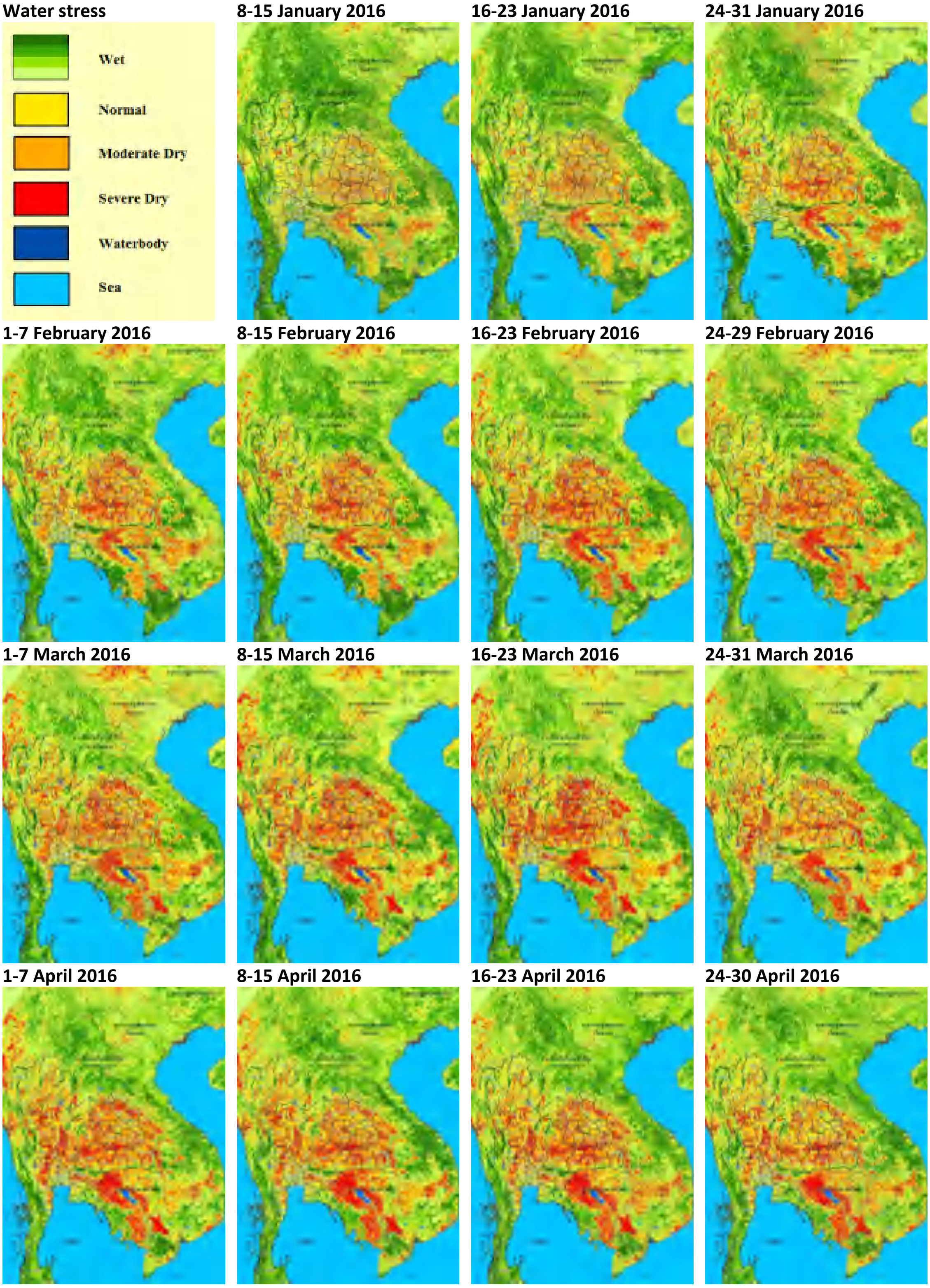


Figure 6.3-4 | Normalised Difference Water Index (Water Stress for Agriculture) from Geo-Informatics and Space Technology Development Agency (GISTDA) for January-April 2016.

6.4 Influence of Lancang cascade reservoir operation on dry season volume of the Mekong River

Overall influence of Lancang cascade reservoir operation on dry season volume of the Mekong River was analysed by comparing long term average of dry season discharge, then converted to volume of 1960-2009 and 2010-2015.

The Xiaowan Reservoir started to store water in the flood season of 2009 with the first power unit put into use in September 2009. During this period, the hydropower plant only functioned to minimum power generation. Until July 2010, the stored water level reached the dead level and the Xiaowan Reservoir began to perform its regulation and storage capacity. Likewise, the Nuozhadu Reservoir started to generate power in September 2012. These two large reservoirs balance the Lancang flows between the rainy and dry seasons with its storage capacity and regulation. Hence, it is widely accepted that Year 2010 is considered as a dividing time point, when considerable influence of the Lancang cascade on flows of the Mekong mainstream in the dry season grows.

6.4.1 Annual volume of the Lancang River

Main cascade reservoirs of the Lancang River were completed between 2010 and 2015. The Gongguoqiao Reservoir started fully operational in 2012, Xiaowan in 2010, Manwan in 2007, Dachaoshan in 2003, Nuozhadu in 2014 and Jinghong in 2009. Therefore, the volume at Jinghong hydrological station before 2009 could be considered as the 'natural condition' without influence of operation of the reservoirs. An amount of 13.0 billion m^3 was reduced at Jinghong, with an average annual volume of 56.2 billion m^3 for 1960-2009 and 43.2 billion m^3 for 2010- 2015.

From 2010 to 2015, Gongguoqiao and Nuozhadu Reservoirs started to store water with a total dead storage of 10.68 billion m^3, which means a contribution of 1.78 billion m^3 annually (10.68 billion m^3 over 6 years of 2010-2015) to the variation of average annual volume at Jinghong. It only represents about 4% (1.78 billion m^3 of 43.2 billion m^3) of average annual volume of 2010-2015. Besides the storage of the Lancang Reservoirs, the average annual volume of 2010-2015 reduced by 11.2 billion m^3 (13.0 billion m^3 minus 1.78 billion m^3), which was about 20% (11.2 billion m^3 of 56.2 billion m^3) of the average value of 1960-2009. This reflects a reduction of 20% of annual volume at Jinghong which is typically caused by climate variability.

6.4.2 Impact of cascade dams on dry season volume of the Mekong River

Using monthly average discharge of 1960-2009 and 2010-2015, average volume for the dry season (Dec-May) was evaluated at Jinghong and seven other hydrological stations along the Mekong River. The results show that the operation of the Lancang cascade dams increased dry season volume at Jinghong from 11.82 billion m^3 (or 21% of annual volume of 1960-2009) to

17.77 billion m^3 (or 41% of annual volume of 2010-2015), contributing 5.95 billion m^3 (or 20%). Likewise, overall increase in dry season volume were observable between 4% and 12% at hydrological stations along the Mekong mainstream, as presented in **Table 6.4-1**. However, it is important to note that the increase was also partly attributed to regional climate condition (rainfall) and contribution from tributaries.

Table 6.4-1 | Average volume for the dry season and its ratio to annual volume along the Lancang-Mekong mainstream

Station	Average volume of the dry season (billion m^3) and ratio to annual volume (%)		
	1960-2009	2010-2015	Increase
Jinghong	11.82 (21%)	17.77 (41%)	5.95 (20%)
Chiang Saen	17.79 (21%)	24.22 (33%)	6.43 (12%)
Luang Prabang	23.99 (19%)	28.15 (27%)	4.17 (7%)
Nong Khai	26.57 (18%)	31.48 (24%)	4.90 (5%)
Nakhon Phanom	34.85 (15%)	45.90 (19%)	11.06 (4%)
Mukdahan	35.59 (14%)	52.59 (20%)	17.00 (5%)
Pakse	41.74 (13%)	56.02 (18%)	14.28 (5%)
Stung Treng	51.41 (13%)	62.06 (17%)	10.65 (4%)

6.5 Hydrological influence of the emergency water supplement to the Mekong River

Hydrological influence of the emergency water supplement in 2016 on water level, discharge and volume of the Mekong mainstream was investigated using monthly average of water level, discharge and volume of the dry season of 2016, 1960-2009 and 2010-2015. Moreover, contribution of volume at Jinghong and from stretch along the Mekong River was also studied.

6.5.1 Influence on discharge of the Mekong River

The monthly average discharge in the dry season from December to May during 2009-2010, 2012-2013 and 2015-2016 at Jinghong and seven key stations along the Mekong mainstream was calculated from daily derived discharge at these stations. Moreover, the monthly average discharges of those dry seasons were compared with average discharge during 1960-2009 and 2010-2015 was conducted. The results of this analysis are presented in **Figure 6.5-1**.

It is observed that flow patterns of 2010-2015 at all interested stations were generally higher than that of 1960-2009. However, pattern of two-month (March and April) minimum discharges of 1960-2009 was typically replaced by one-month (February) minimum flows of 2010-2015.

Particularly for the dry season of 2016, it is found that discharges in December 2015 at all stations, except for Jinghong and Mukdahan, were lower than the average discharges of 1960-2009. This was because of low inflows to the Lancang-Mekong River during this month. In January 2016, discharges at most stations were between the average discharges of 1960-2009 and 2010-2015, while discharges at Jinghong were higher than those of 2010-2015 and discharges at Nong Khai and Stung Treng were lower than those of 1960-2009. Furthermore, discharges in February 2016 at stations downstream Chiang Saen were above the average discharge of 2010-2015. This observable pattern happened as there was a bump of flows at Jinghong in mid-January and that bump travelled down the Mekong mainstream. It is important to note that February was considered as the lowest month of the dry season as reflected in the general pattern of the dry season of 2010-2015. Additionally, discharges for March-April 2016 at most stations were higher than average discharge of 2010-2015, indicating the implementation of the emergency water supplement from China. Finally, discharges in May 2016 at all stations, except at Jinghong, were between the average of 1960-2019 and 2010-2015.

Among the three drought events of 2009-2010, 2012-2013, and 2015-2016, the discharges of 2009-2010 were generally lowest and lower than the long-term averages between 1960 and 2009. The drought condition in 2012-2013 and 2015-2016 seems to have similar effect in term of flow discharge from December to March with an exemption in March for upstream locations from Jinghong to Nong Khai where the situation was better in 2015-2016 as a result of emergency water supplement from China. The discharges in April 2016 were not surprisingly higher than all drought events at all locations before dropped in May 2016 lower than the 2012-2013 event but still higher than that of 2009-2010.

During the period of the emergency water supplement in March and April 2016, the monthly average discharges at Jinghong were 1,280 m^3/s and 985 m^3/s, respectively, larger than the average of 1960-2009, and 704 m^3/s and 442 m^3/s larger than the average of 2010-2015. Meanwhile, discharges at key stations along the Mekong mainstream were also increased to a different extent, as shown in **Table 6.5-1**. Therefore, with a proper operation of the Lancang cascade dams, the discharge along the Mekong mainstream increased considerably in these two months of March-April, which were the period of minimum discharge for 1960-2009. More specifically, monitoring records in 2016 reveal a further increase in discharge even higher than the average of 2010-2015. This implies the emergency water supplement undoubtedly helps mitigate the prolonged meteorological and agricultural droughts in the Mekong Basin.

Table 6.5-1 | Monthly average discharge in March and April 2016 and average increased discharge comparing to the average discharge of 1960-2009 and 2010-2015

Station	Discharge for 2016 (m^3/s)		Increased discharge comparing to 1960-2009		Increased discharge comparing to 2010-2015	
	March	April	March	April	March	April
Jinghong	1,830	1,660	1,280	985	704	442
Chiang Saen	1,860	1,720	1,020	806	427	231
Luang Prabang	1,930	1,900	871	789	394	307
Nong Khai	1,960	2,030	782	789	282	287
Nakhon Phanom	2,650	3,080	1,070	1,510	234	588
Mukdaham	3,140	3,620	1,520	2,000	259	610
Pakse	2,990	3,710	1,120	1,860	113	632
Stung Treng	2,960	3,710	774	1,570	-80	344
Kratie	2,7170	3,412	6724	1,421	-294	125

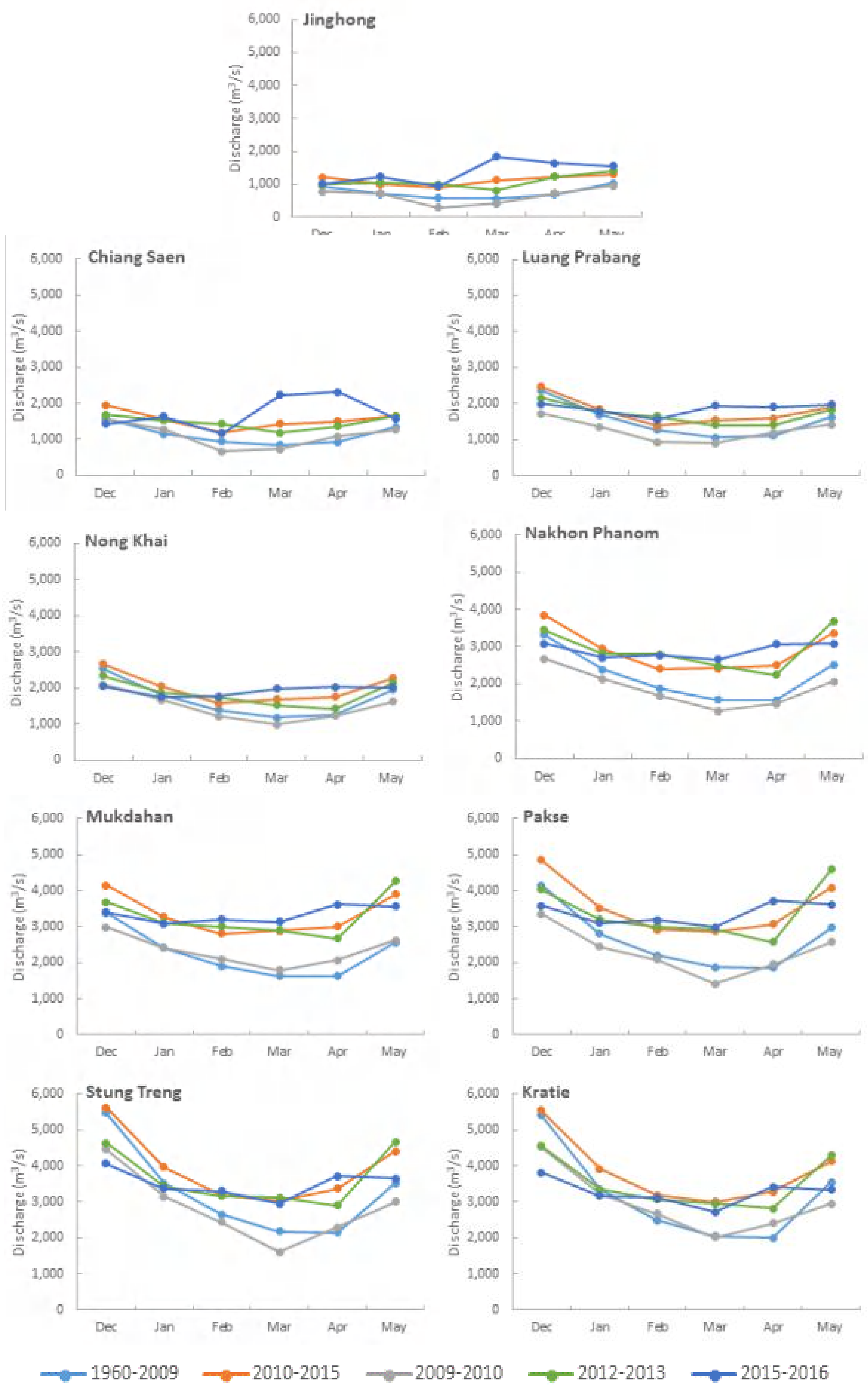


Figure 6.5-1 | Comparison of monthly average discharge along the Lancang-Mekong mainstream for the periods 2009-2010, 2010-2015 and the dry seasons of 2009-2010, 2012-2013, and 2015-2016.

6.5.2 Influence on water level of the Mekong River

For the purposes of comparison between the long term average of 1960-2009 and 2010-2015, the monthly average water level in the dry season of 2016 (December 2015 to May 2016) along the Lancang-Mekong mainstream was calculated from the daily water level and the results are presented in **Table 6.5-2**.

In December 2015, the water levels at most stations along the Lancang-Mekong River were generally lower than the average value of 1960-2009. However, from January to May 2016, the water levels at all stations were typically higher than the average of 1960-2009. As shown in **Table 6.7-1**, water level in March 2016 at the hydrological stations rose to an overall extent of 0.18-1.53 m.

Table 6.5-2 | Monthly average water level in the dry season of 2016 and deviation of average water levels of 2016, 1960-2009 and 2010-2015

Station	December	January	February	March	April	May
Average water level in 2016 (m local datum)						
Jinghong	535.54	535.82	535.43	536.62	536.43	536.36
Chiang Saen	2.38	2.47	2.05	2.84	2.70	2.53
Luang Prabang	4.99	4.60	4.19	4.89	4.83	4.84
Nong Khai	2.29	1.88	1.78	2.16	2.25	2.07
Nakhon Phanom	1.88	1.59	1.56	1.54	1.87	1.66
Mukdahan	2.09	1.89	1.92	1.92	2.22	2.01
Pakse	1.50	1.27	1.29	1.21	1.56	1.35
Stung Treng	2.81	2.61	2.59	2.48	2.71	2.57
Kratie	7.64	7.16	7.12	6.80	7.35	7.28
Deviation of average water level between 2016 and 1960-2009 (m)						
Jinghong	-0.15	0.62	0.47	1.73	1.32	0.66
Chiang Saen	0.16	0.82	0.77	1.74	1.46	0.63
Luang Prabang	-0.64	0.03	0.37	1.52	1.38	0.47
Nong Khai	-0.76	-0.29	0.18	0.90	0.91	-0.16
Nakhon Phanom	-0.47	0.00	0.41	0.63	0.94	-0.09
Mukdahan	-0.41	0.03	0.41	0.61	0.93	0.11
Pakse	-0.43	0.01	0.35	0.46	0.82	0.04
Stung Treng	-0.33	0.03	0.32	0.41	0.68	0.05
Kratie	-0.32	0.61	1.34	1.51	2.25	1.15
Deviation of average water level between 2016 and 2010-2015 (m)						
Jinghong	-0.29	0.33	0.23	1.00	0.63	0.35
Chiang Saen	-0.52	-0.03	0.01	0.53	0.29	-0.06
Luang Prabang	-0.65	-0.10	0.31	0.77	0.58	0.04
Nong Khai	-0.67	-0.38	0.17	0.45	0.43	-0.46
Nakhon Phanom	-0.47	-0.17	0.22	0.22	0.48	-0.38
Mukdahan	-0.40	-0.10	0.22	0.19	0.41	-0.35
Pakse	-0.55	-0.19	0.12	0.07	0.31	-0.37
Stung Treng	-0.42	-0.17	0.04	-0.02	0.11	-0.33
Kratie	-1.09	-0.52	-0.05	-0.22	0.12	-0.55

6.5.3 Influence on volume of the Mekong River

Accumulated volume in the dry season of 2016 at Jinghong was 21.69 billion m^3, with an average increase of 3.92 billion m^3 and 9.87 billion m^3 over the long term average of 2010-2015 and 1960-2009, respectively. Moreover, the accumulated volume in the dry season of 2016 at other stations along the Mekong mainstream was larger than the long term average of 1960- 2009.

Table 6.5-3 shows that the accumulated volume in the dry season of 2016 and its deviation between that of 2010-2015 and 1960-2009.

Since the emergency water supplement was implemented by increasing the discharge of Jinghong Reservoir, the accumulated volume from Lancang River in the dry season of 2016 occupied a larger percentage of the volume in the Mekong River than the past years. The ratio, at which the accumulated volume at Jinghong occupied the volume at different stations along the Mekong mainstream, is presented in

Table 6.5-3. The accumulated volume in the dry season of 2016 at Jinghong presented huge portion (40%-89%) of the accumulated volume at different stations along the Mekong mainstream. Furthermore, it is considered that the increase in volume in the Mekong River was 20% and 10%, compared to average accumulated volume of 1960-2009 and 2010-2015, respectively.

The stretch between Jinghong and Chiang Saen provided similar order of average contribution in 1960-2009 and 2010-2015, as indicated in **Table 6.5-4**. However, it is obviously seen that this stretch generated relatively low flow in the dry season of 2016. Furthermore, several tributaries on the left bank of the Mekong River between Chiang Saen and Luang Prabang contributed to volume in the mainstream.

Additionally, contribution from the stretch between Luang Prabang and Nong Khai was barely changed for 1960-2009 and 2010-2015 and flows in the dry season of 2016 were noticeably low.

For the stretch between Nong Khai and Nakhon Phanom, there are many large tributaries from the left bank of the Mekong mainstream, including Nam Ngum. This major water producing area contributed substantial flows to the mainstream. The volumes in the dry season for 2010-2015 and 2016 were found to increase when comparing to the average volumes of 1960-2009.

Although the section between Nahkon Phanom to Mukdahan has only a small catchment of about 1,800 km2, and produced relatively small amount of contribution in the dry season of 1960-2009, the water yield of 2010-2015 and 2016 was found about 9 times higher than the average of 1960-2009. It is suggested that hydrological data and rating curves of 1960-2009 at these two stations should be carefully revisited.

Flows of the mainstream of the stretch between Mukdahan and Stung Treng come from two major tributaries of the Mun-Chi of the right bank and Sekong-Sesan-Srepok of the left bank. This section was traditionally water producing areas, however, the water volume produced in the dry season of 2010-2015 and 2016 was found to be less than the average 1960-2009, particularly in 2016.

Table 6.5-3 | Volume in the dry season of 2016, 1960-2009 and 2010-2015 along the Lancang-Mekong mainstream

Station	Volume of the dry season (billion m^3)			Deviation of volume between (billion m^3)		
	1960-2009 (% Jinghong)	2010-2015 (% Jinghong)	2016 (% Jinghong)	2016 and 1960-2009	2016 and 2010-2015	2010-2015 and 1960-2009
Jinghong	11.82 (100%)	17.77 (100%)	21.69 (100%)	9.87	3.92	5.95
Chiang Saen	17.79 (66%)	24.22 (73%)	24.33 (89%)	6.54	0.11	6.43
Luang Prabang	23.99 (49%)	28.15 (63%)	28.94 (75%)	4.95	0.79	4.17
Nong Khai	26.57 (44%)	31.48 (56%)	29.90 (73%)	3.33	-1.57	4.90
Nakhon Phanom	34.85 (34%)	45.90 (39%)	44.66 (49%)	9.81	-1.25	11.06
Mukdahan	35.59 (33%)	52.59 (34%)	51.69 (42%)	16.10	-0.90	17.00
Pakse	41.74 (28%)	56.02 (32%)	52.01 (42%)	10.28	-4.01	14.28
Stung Treng	51.41 (23%)	62.06 (29%)	54.19 (40%)	2.78	-7.88	10.65

Table 6.5-4 | Contribution of volume in the dry season of 2016, 1960-2009 and 2010-2015 at different stretch along the Lancang-Mekong mainstream

Stretch between	Volume of the dry season (billion m^3)			Deviation of volume between (billion m^3)		
	1960-2009	2010-2015	2016	2016 and 1960-2009	2016 and 2010-2015	2010-2015 and 1960-2009
Jinghong and Chiang Saen	5.97	6.45	2.63	-3.33	-3.81	0.48
Chiang Saen and Luang Prabang	6.20	3.94	4.61	-1.58	0.68	-2.26
Luang Prabang and Nong Khai	2.59	3.32	0.96	-1.62	-2.36	0.73
Nong Khai and Nakhon Phanom	8.27	14.43	14.76	6.48	0.33	6.15
Nakhon Phanom and Mukdahan	0.74	6.69	7.03	6.29	0.34	5.95
Mukdahan and Pakse	6.15	3.43	0.33	-5.82	-3.10	-2.72
Pakse and Stung Treng	9.67	6.04	2.17	-7.50	-3.87	-3.63

During the emergency water supplement from 10 March to 10 April 2016 (32 days), discharges at Jinghong stayed at about 2,000 m^3/s, with an accumulated volume of 6.00 billion m^3. Taking the travelling time into consideration, ratio at which the volume at Jinghong contributes to the total accumulated volume of the hydrological stations was calculated. The results are shown in **Table**

6.5-5. The total accumulated volume at Stung Treng is found to be 10.30 billion m^3 for the period between 27 March and 27 April (moving band of 32 days). Thus, the volume of the emergency water supplement in 2016 at Jinghong claims 58% of that at Stung Treng.

Table 6.5-5 | Contribution of accumulated volume at Jinghong to that at stations along the Mekong mainstream during the emergency water supplement of 2016

Station	Travelling time	Moving band of 32 days	Discharge (m^3/s)	Volume (billion m^3)	Ratio of Jinghong
Jinghong	+0 day	10 Mar to 10 Apr	2,170	6.00	100%
Chiang Saen	+1 day	11 Mar to 11 Apr	2,199	6.08	99%
Luang Prabang	+4 days	14 Mar to 14 Apr	2,237	6.18	97%
Nong Khai	+9 days	19 Mar to 19 Apr	2,361	6.53	92%
Nakhon Phanom	+12 days	22 Mar to 22 Apr	3,262	9.02	67%
Mukdahan	+13 days	23 Mar to 23 Apr	3,748	10.36	58%
Pakse	+15 days	25 Mar to 25 Apr	3,781	10.45	57%
Stung Treng	+17 days	27 Mar to 27 Apr	3,726	10.30	58%

6.6 Net contribution of the emergency water supplement to discharge of the Mekong River

Major influential factors of flows of the Mekong mainstream considered in this study are rainfall, water supplement from China, water releases from water infrastructure in the Mekong Basin, water withdrawal along the Mekong mainstream.

It is understood that only small amount of rainfall was observed over the Mekong Basin. Additionally, since data and information of water releases from water infrastructures in the Mekong Basin and water withdrawal along the Mekong mainstream were not available at the time of this analysis, it is considered that the water supplement was a lumped sum of the emergency water supplement from China, lateral inflow and outflow of the Lancang-Mekong mainstream.

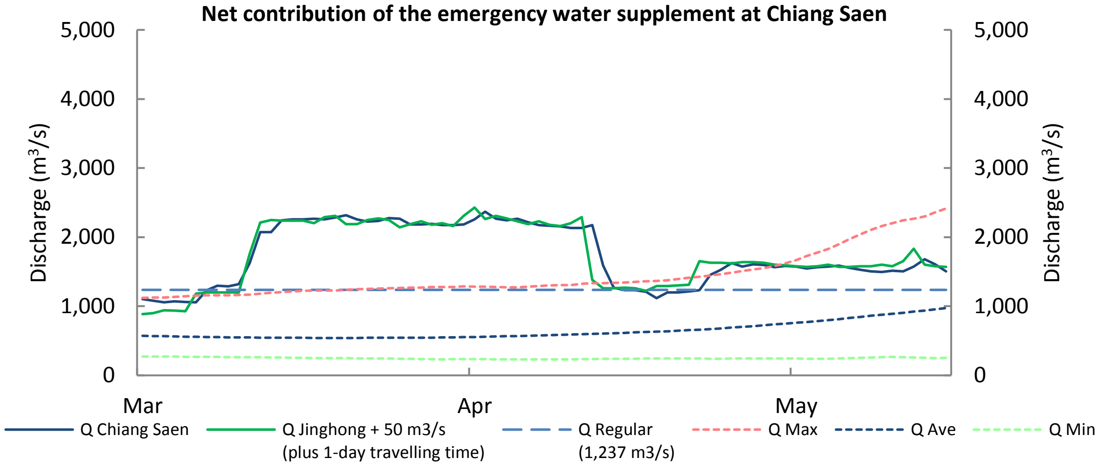
Analysis of the influential factors of flows of the Mekong mainstream was performed using hydrograph separation and hydrograph adjustment during the period of the emergency water supplement of March-May 2016. A simple hydrograph separation method[22] was applied by drawing a horizontal line between the beginning of rising limb of the hydrograph, which marked the arrival of the water supplement, and the end of falling limb of the hydrograph. This method was used to separate discharge of the water supplement from 'regular discharges'. On the other hand, the hydrograph at Jinghong was adjusted using discharge offset and travelling time to the hydrograph at Chiang Sean, Nong Khai and Stung Treng. These two methods were used for a cross-check in this analysis. It is found that discharge difference between these methods at all

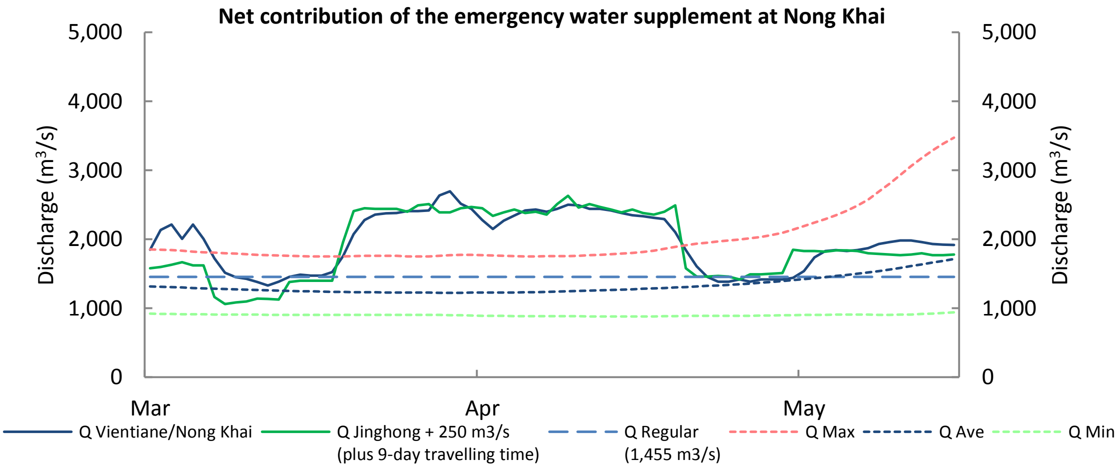
[22] Gupta R. S. 2008, Hydrology and Hydraulic System, Third Edition, Waveland Press, United States.

selected stations was relatively small and within the error margin of the accuracy of its rating curves[23]. Results of the analysis are illustrated in **Figure 6.6-1** and summarised in **Table 6.6-1**.

Examining the hydrograph at Jinghong for March-May 2016 reveals that there were two distinct bands of the emergency water supplement from China: (1) steady flows of 2,200 m^3/s from 10 March to 10 April 2016 and (2) steady flows of 1,500 m^3/s from 21 April to 31 May 2016. These bands propagated along the Mekong mainstream as seen at Chiang Saen, Nong Khai and Stung Treng (**Figure 6.6-1**). The first band of 32 days was particularly investigated. Net contribution of the emergency water supplement at a given station was evaluated as a difference between average discharges of the moving band and the 'regular discharges' at the station (**Table 6.6-1**). The net contribution of the emergency water supplement is found to be 1,024 m^3/s (or 47% of total discharges during the water supplement) at Jinghong, 962 m^3/s (or 44%) at Chiang Saen, 906 m^3/s (or 38%) at Nong Khai, and 818 m^3/s (or 22%) at Stung Treng.

[23] Difference between hydrograph separation and hydrograph adjustment is found: 91 m^3/s – 50 m^3/s = 41 m^3/s and Root Mean Square Error (RMSE) of the rating curve of 158 m^3/s (75 measurement points with discharge ranging between 720 m^3/s and 6,977 m^3/s) at Chiang Saen; 309 m^3/s – 250 m^3/s = 59 m^3/s and RMSE of 400 m^3/s (85 points with discharge ranging between 884 m^3/s and 15,928 m^3/s) at Nong Khai; and 1,762 m^3/s – 1,650 m^3/s = 112 m^3/s and RMSE of 328 m^3/s (129 points with discharge ranging between 2,232 m^3/s and 39,971 m^3/s) at Stung Treng.





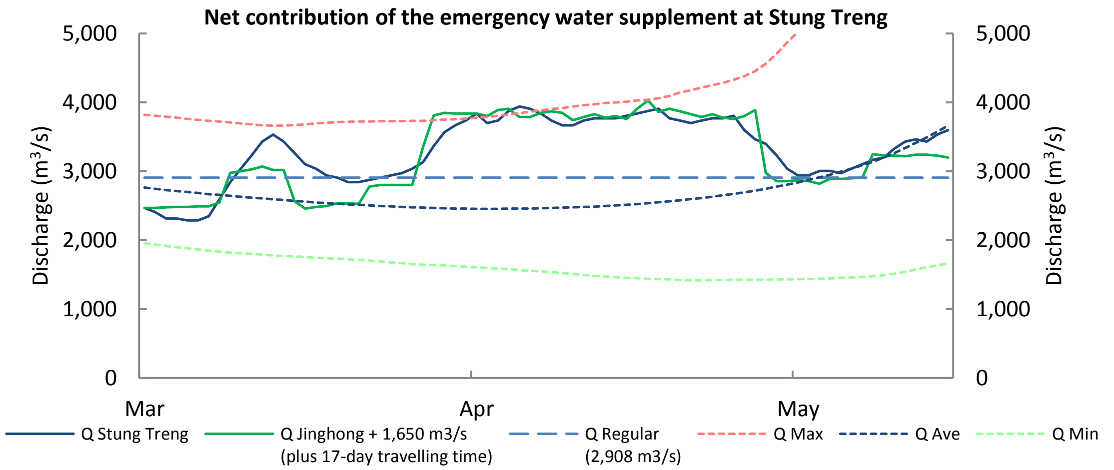


Figure 6.6-1 | Net contribution of the emergency water supplement at Chiang Saen, Nong Khai and Stung Treng from 1 March to 15 May 2016.

Water supplement is a lumped sum of the emergency water supplement from China, lateral inflow and outflow of the Lancang-Mekong mainstream during the investigation period. Q Max, Q Ave and Q Min are the maximum, average and minimum of historical records of 1962-2009.

Table 6.6-1 | Analysis of net contribution of the emergency water supplement at Chiang Saen, Nong Khai and Stung Treng for March-May 2016

Water supplement is a lumped sum of the emergency water supplement from China, lateral inflow and outflow of the Lancang-Mekong mainstream during the investigation period.

Hydrograph separation for 'regular discharges' at	Discharge (m^3/s)
Jinghong (5 days: 5-9 Mar)	1,146
Chiang Saen (5 days: 6-10 Mar)	1,237
Nong Khai (5 days: 13-17 Mar)	1,455
Stung Treng (5 days: 21-25 Mar)	2,908
Difference of 'regular discharge' between	
Jinghong and Chiang Saen	91
Jinghong and Nong Khai	309
Jinghong and Stung Treng	1,762
Contribution of catchment area between	
Jinghong and Chiang Saen	91
Chiang Saen and Nong Khai	218
Nong Khai and Stung Treng	1,453
Hydrograph adjustment between	
Jinghong and Chiang Saen (travelling time: +1 day)	50
Jinghong and Nong Khai (travelling time: +9 days)	250
Jinghong and Stung Treng (travelling time: +17 days)	1,650
Average discharge of the moving band of the emergency water supplement at	
Jinghong (32 days: 10 Mar to 10 Apr)	2,170
Chiang Saen (32 days: 11 Mar to 11 Apr)	2,199
Nong Khai (32 days: 19 Mar to 19 Apr)	2,361
Stung Treng (32 days: 27 Mar to 27 Apr)	3,726
Net contribution and ratio to total discharges during the water supplement at	
Jinghong	1,024 (47%)
Chiang Saen	962 (44%)
Nong Khai	906 (38%)
Stung Treng	818 (22%)

6.7 Flow propagation along the Mekong mainstream

Flow propagation along the Mekong mainstream was conducted using variation of daily water level and discharge, and sequence of its events, including the emergency water supplement. Variation of water level and discharge at Jinghong during the emergency water supplement was generally planned as follows:

- 9 to 11 March 2016 – increasing to 2,000 m^3/s;
- 12 March to 10 April 2016 – staying at 2,200 m^3/s;

- 11 to 12 April 2016 – decreasing to 1,200 m^3/s;
- 13 to 20 April 2016 – staying at 1,200 m^3/s;
- 21 April 2016 – increasing to 1,500 m^3/s; and
- 22 April to 31 May 2016 – staying at 1,500 m^3/s.

As shown in **Figure 6.7-1**, the discharge at Jinghong from March 9 to March 11 was gradually increased to 2,160 m^3/s, with an obvious rise of water level from 535.76 m to 537.05 m. For an analysis on the travelling time, the beginning time of the emergency water supplement was thus deemed as 9 March 2016.

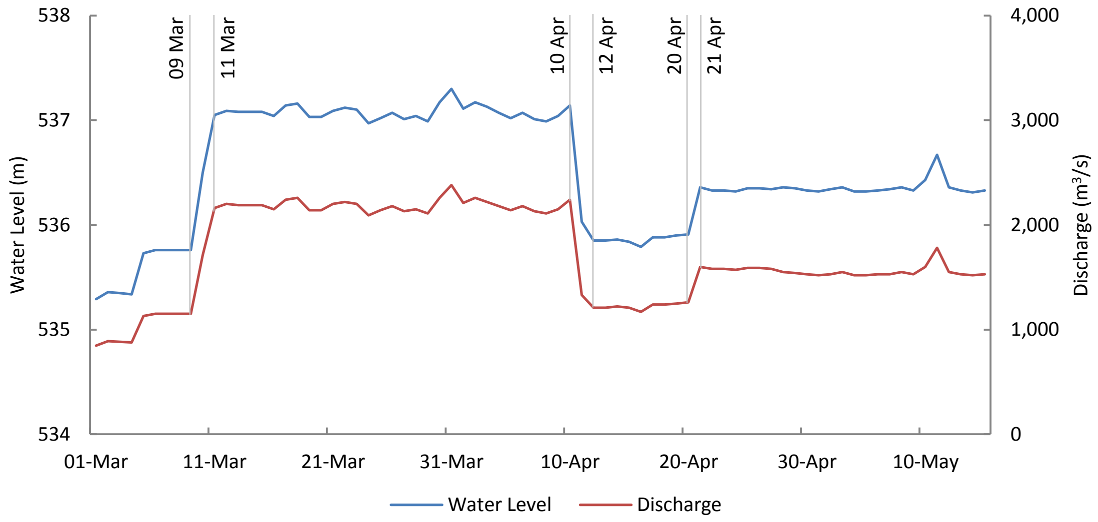


Figure 6.7-1 | Variation of daily water level and discharge at Jinghong from 1 March to 15 May 2016.

Propagation of the flow pattern along the mainstream was investigated using daily observed water level at 22 hydrological stations (1 station in the Lancang River and 21 stations in the Mekong River) and discharge at 8 hydrological stations (1 in the Lancang River and 7 in the Mekong River). Rated discharge was derived from the observed water level using newly developed rating curves by taking advantages of 'Discharge and Sediment Monitoring Project for 2008-2014', implemented by the MRC's Information and Knowledge Management Programme (IKMP).

For general flow conditions, characteristics of rapid fluctuation of daily observed water level and rated discharge of the Mekong mainstream for the dry season between Chiang Saen to Pakse follows the flow pattern observed in Chiang Saen. This is because the flow pattern is not typically perturbed by runoff generated from intense rainfall, which does not usually occur in

the basin during the dry season. The pattern becomes smoother and less variable as the Mekong River entering Cambodia, at Stung Treng since the flows from the Tonle Sap Lake dominated the flows in the Mekong River during this period. For particular dry season flow conditions of 2016, where flow volume stored in the Tonle Sap Lake was relatively low, patterns of variation of daily water level and discharge observed at Chiang Saen could be still seen at Tan Chau and Chau Doc (**Figure 6.7-2**).

The emergency water supplement arrived at Chiang Saen on 11 March and started increasing till 14 March (3 days). As presented in **Table 6.7-1** and depicted in **Figure 6.7-2** and **Figure 6.7-3**, this pattern reached Luang Prabang on 14 March, Chiang Khan on 17 March, Nong Khai on 19 March, Nakhon Phanom on 22 March, Mukdahan on 23 March, Pakse on 25 March, Stung Treng on 27 March and Kratie on 28 March 2016.

Due to flow conditions downstream Kratie are normally influenced by the outflow of the Tonle Sap Lake and tide of the sea, using variation of water level to mark arrival time of the emergency water supplement in this area is not obvious. It took 18 days for the emergency supplement water to travel a total length of 2,147 km from Jinghong to Kratie. Thus, this suggested a moving velocity of 1.4 m/s (or 5 km/h). It is assumed that the moving velocity was slowed down to 1 m/s in floodplain area. It would take around 4 days to travel 324 km between Kratie and Tan Chau. This is therefore believed that the emergency water supplement arrived to Tan Chau on 1 April 2016 with a travelling time from Jinghong of 22 days.

Moreover, monitoring at Chiang Khan suggests that additional water of 300 m^3/s for one day on top of the emergency water supplement was detected on 27 March 2016. This additional water arrived at Nong Khai on 28 March, at Nakhon Phanom on 31 March, at Mukdahan on 1 April, at Pakse on 3 April and at Stung Treng on 4 April. Immediately after the peak of the additional water at Chiang Khan, a drop in flows of 300 m^3/s was recorded on 31 March 2016.

Table 6.7-1 | Propagation of the emergency water supplement of 2016 along the Mekong mainstream

Station	River kilometre	Water supplement arrival	Variation*	Increment
Jinghong	2,707 km	10 to 11 March (+0 day)	535.76 m (1,150 m^3/s) to 537.05 m (2,160 m^3/s)	+1.29 m (+1,010 m^3/s)
Chiang Saen	2,364 km	11 to 14 March (+1 day)	2.26 m (1,319 m^3/s) to 3.27 m (2,245 m^3/s)	+1.01 m (+926 m^3/s)
Luang Prabang	2,010 km	14 to 17 March (+4 days)	4.06 m (1,454 m^3/s) to 5.50 m (2,295 m^3/s)	+1.44 m (+841 m^3/s)
Chiang Khan	1,715 km	17 to 20 March (+7 days)	3.91 m to 5.44 m	+1.53 m
Nong Khai	1,549 km	19 to 22 March (+9 days)	1.57 m (1,526 m^3/s) to 2.70 m (2,359 m^3/s)	+1.13 m (+833 m^3/s)
Nakhon Phanom	1,221 km	22 to 25 March (+12 days)	1.35 m (2,385 m^3/s) to 1.95 m (3,183 m^3/s)	+0.60 m (+798 m^3/s)
Mukdahan	1,128 km	23 to 26 March (+13 days)	1.85 m (3,024 m^3/s) to 2.29 m (3,729 m^3/s)	+0.44 m (+705 m^3/s)
Pakse	866 km	25 to 28 March (+15 days)	1.20 m (2,954 m^3/s) to 1.58 m (3,743 m^3/s)	+0.38 m (+789 m^3/s)
Stung Treng	683 km	27 to 31 March (+17 days)	2.54 m (3,135 m^3/s) to 2.72 m (3,737 m^3/s)	+0.18 m (+602 m^3/s)
Kratie		28 March to 1 April (+18 days)	6.93 m to 7.23 m	+0.30 m

* Variation of daily observed water level or rated discharge starts one-day earlier than the arrival of the emergency water supplement.

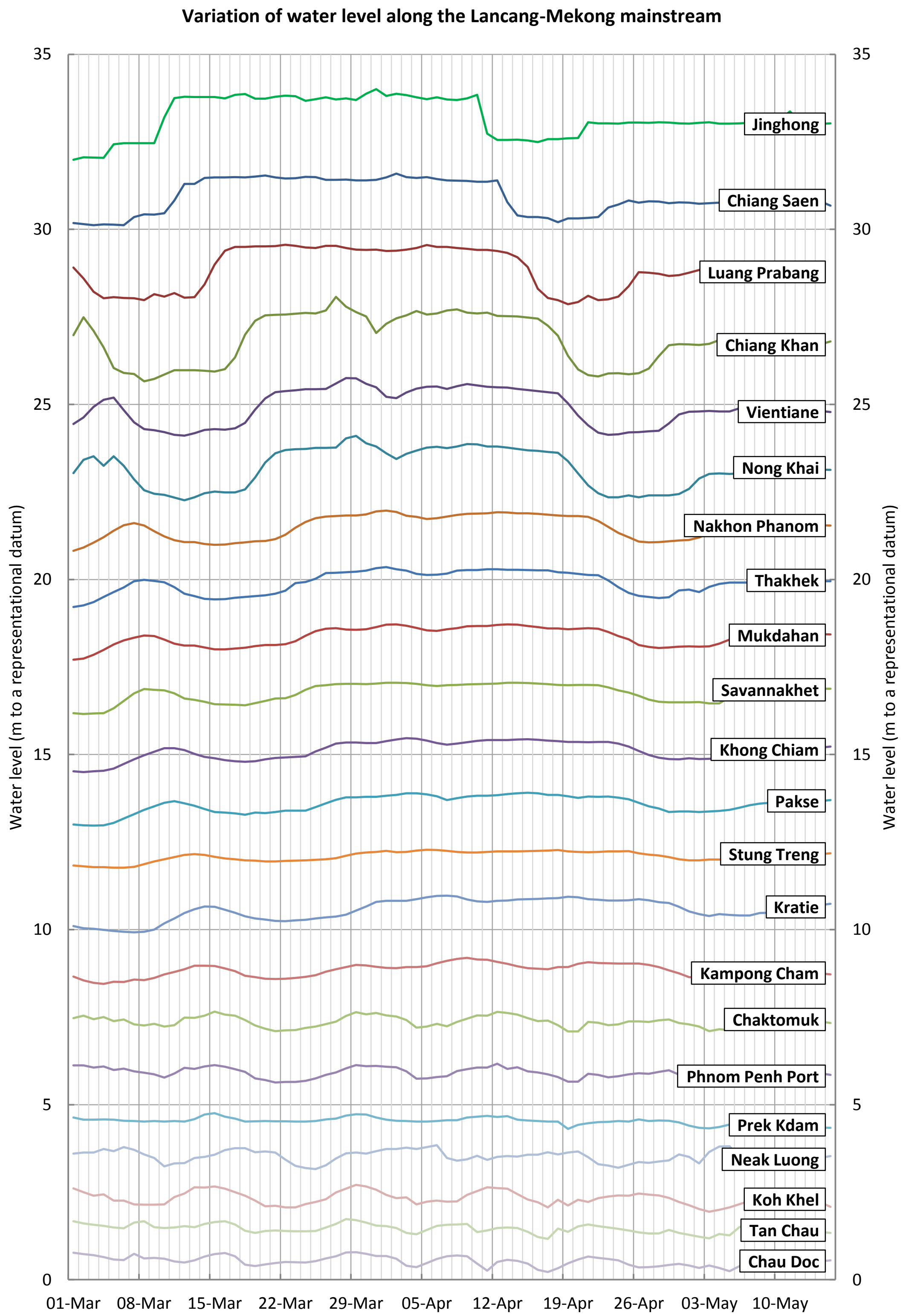


Figure 6.7-2 | Propagation of daily water level along the Lancang-Mekong mainstream for March-May of 2016.

It is critically important to note that water level is referenced to a representational datum for presentation purposes only.

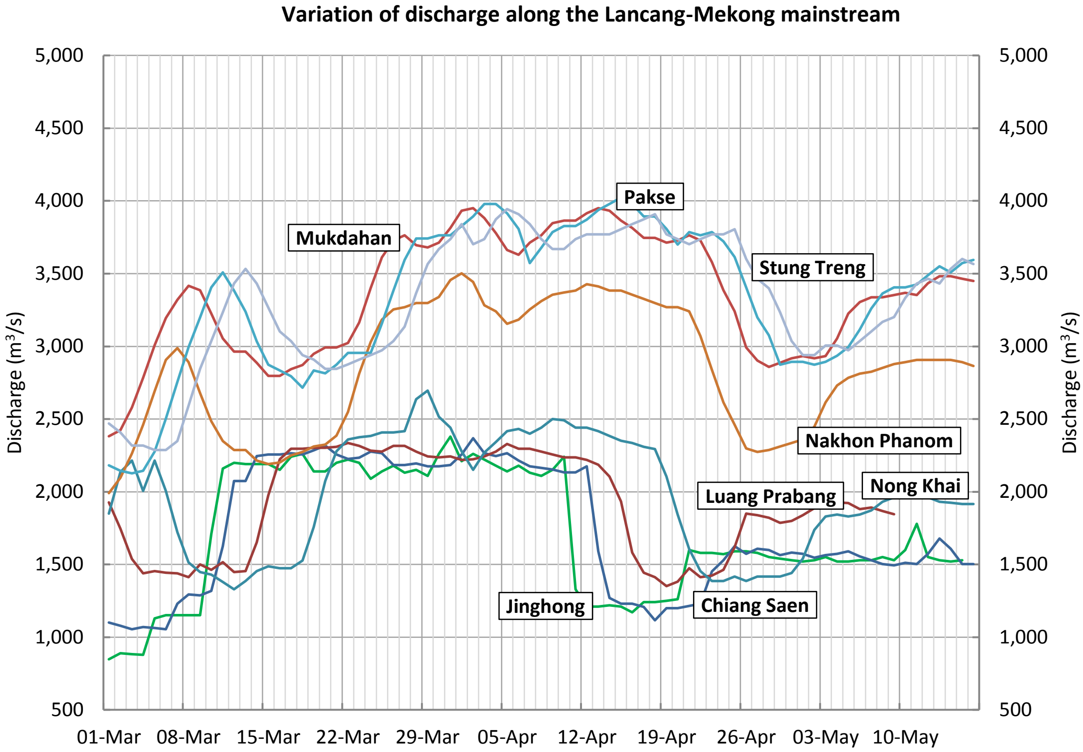


Figure 6.7-3 | Propagation of daily discharge at some selected hydrological stations along the Lancang- Mekong mainstream for March-May 2016.

6.8 Salinity variation in the Mekong Delta

As adequate data and information on benefits of the emergency water supplement on reducing the meteorological agricultural drought affected area were not available at the time of this study, general observation of the benefits of easing the drought was compiled using various sources as presented in Annex A. Thus, analysis in this section was limited to salinity variation at in Soc Trang Province.

Soc Trang Province locates 231 km from Ho Chi Minh city, 60 km from Can Tho, close to Tra Vinh, Vinh Long, Hau Giang, Bac Lieu, with coastline of 72 km coastline and alluvial flat of 30,000 ha. It has an ocean climate and two seasons, rainy season from May to November, and dry season from December to May. The average temperature is between 26°C and 28°C. The economy is agriculture dominated, with cropland of 259,799 ha, among which 94% is rice field. The other cropland is covered by maize, Mung beans, jackfruit, coconut trees, green onion and garlic etc.

Salinity intrusion distance reached up to 80 km in March 2016 in Soc Trang Province. There are seven salinity monitoring stations in Soc Trang Province, namely Tran De, Long Phu, Dai Ngai, An Lac Tay on the main river, Soc Trang city, Nga Nam and Than Phu on canals. Tran De locates near the river mouth and An Lac Tay is about 40 km from the river mouth (**Figure 6.8-1**).

Salinity variation in the Mekong Delta during the period of the emergency water supplement was analysed using daily maximum and minimum salinity concentration at the seven monitoring sites in the Mekong Delta. Based on the results of flow propagation analysis, the water supplement from the Lancang reservoirs reached the Mekong Delta in early April 2016. The salinity of March and April were compared at An Lac Tay, Dai Ngai , Long Phu, Tran De and Soc Trang city. **Figure 6.8-2** shows that there was a 4-day low salinity at early April at all the stations, though it was in rising tide period. The maximum salinity in April was between 2.2‰ and 6.4‰ less than that in March. The most prominent reduction occurred at An Lac Tay, from 8.0‰ in March to 2.1‰ in April (**Table 6.8-1**). The maximum salinity at Dai Ngai decreased from 13.8‰ in March to 7.4‰ in April. The maximum salinity decreased by 15% and 74%, and the minimum salinity decreased by 9% and 78% according to observation stations. Hence, the emergency water supplement from China contributed in controlling seawater intrusion and reducing salinity, which would help protect ecosystem and environment in the Mekong Delta.

Table 6.8-1 | Observation of salinity in March and April 2016 in Soc Trang Province

Salinity (‰)	Tran De		Long Phu		Dai Ngai		An Lac Tay		Soc Trang City	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Salinity in March	27.4	5.6	23.1	4.1	13.8	0.9	8.0	0	9.0	3.0
Salinity in April	23.4	5.1	17.2	1.4	7.4	0.2	2.1	0	6.8	1.2
Salinity reduction	-4	-0.5	-5.9	-2.7	-6.4	-0.7	-5.9	0	-2.2	-1.8
Reduction ratio	-15%	-9%	-26%	-66%	-46%	-78%	-74%	-	-24%	-60%

Figure 6.8-1 | Salinity monitoring stations in the Mekong Delta.

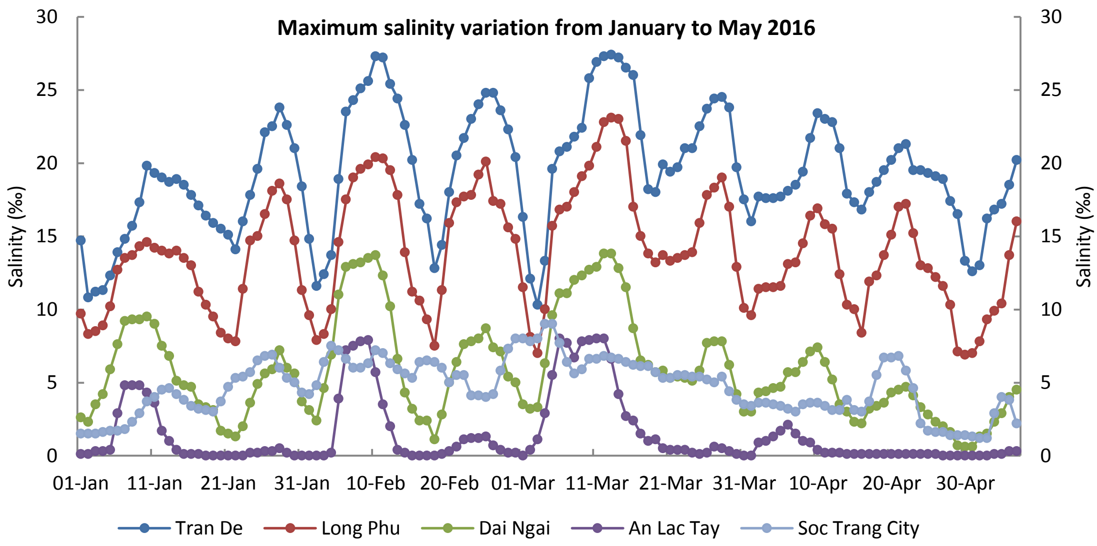


Figure 6.8-2 | Maximum salinity variation from 1 January to 6 May 2016 at the monitoring stations in the Mekong Delta.

7 Analysis of the respective hydrological impacts of climate variability and hydropower operation

This chapter is prepared by the IWMI which is organized as follows: the materials and methods is first presented for the datasets used, data quality control and preprocessing, and the hydrological model development. Results are presented next followed by a discussion on how results compare to previous hydrological assessments of dams in the Lancang-Mekong Basin.

7.1 Materials and Methods

To differentiate the effects of actual hydropower dam operation and climate variability on streamflow, discharge data was analyzed before dam development (before 2009) and compared it to post dam development (after 2009). Our analysis was based on two approaches:

1. Visual and statistical comparison of dry season flow for each hydrological year[24] from 2009/2010 to 2015/2016 with the range of daily flow values observed between hydrological years 1998/1999 and 2007/2008,
2. Using a hydrological model calibrated over the pre-dam period (1998-2008), we simulated streamflow using rainfall from the second period (2010-2016) and compared with flow observed over the same period. Any difference between observed and simulated flow would then be attributed to non-climatic drivers of hydrologic change such as hydropower operation. This analysis was particularly focused on the dry season (October-May) of hydrologic years 2009/2010, 2012/2013 and 2015/2016.

Rainfall data comprised daily records from 112 gauging stations throughout the Lower Mekong Basin (**Figure 7.1-1**) covering the period 1981-2016. Missing rainfall data at the stations for the period 2000-2016 ranged 0-94% with an average of 43% of the data missing across the area. Since the data were not available continuously (temporally and spatially) over the entire study period, we used it to select the most representative temporally continuous gridded rainfall product for the basin for hydrological modelling. Three gridded rainfall products were initially considered: the Asian Precipitation Highly-Resolved Observation Data Integration Towards Evaluation of Water Resources (APHRODITE) which had been used in previous Mekong studies (Lacombe et al., 2014; Lyon et al., 2017), the Tropical Rainfall Measurement Mission (TRMM), and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). However, initial data screening led us to discard the APHRIODITE product since the coverage period was only up to 2007. TRMM is a satellite dedicated to rainfall measurements. It carries 3 rainfall sensors: a Radar sensor (PR), passive microwave Imager (TMI) and a (iii) a visible/infrared (VIS/TIR) sensor to estimate rainfall values. The TRMM (TMPA/3B43) data is available from 1998-2018 at sub-daily, daily and monthly temporal resolution with a spatial resolution of 0.25°. CHIRPS combines long-term monthly mean station data (CHPclim) and local calibration of 0.05° satellite data (CHIRP).

[24] A hydrological year in this study is defined as beginning June 1 and ending May 31 of the following calendar year.

The CHPclim data and CHIRP data are then combined using a modified inverse distance weighting blending procedure to generate gridded maps of rainfall estimates CHIRPS (Funk et al., 2015). The CHIRPS data is available from 1981-present at 6-hourly to 3 monthly aggregate temporal resolution and a spatial resolution of 0.05°.

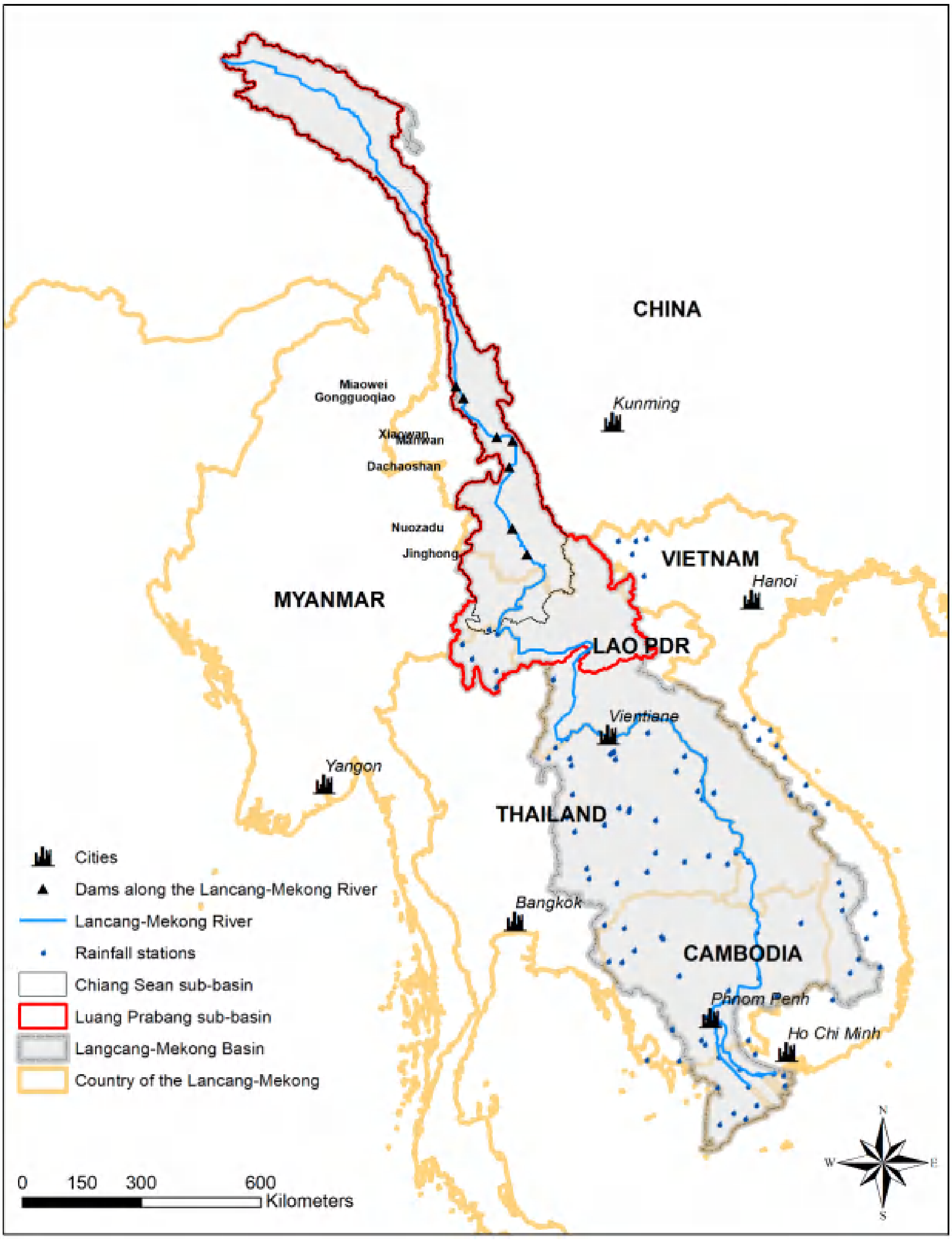


Figure 7.1-1 | Lancang-Mekong River Basin showing location of national borders, main cities, rainfall stations, dams constructed along main stem of the river and sub-basin boundaries at Chiang Sean and Luang Prabang

The selection of the appropriate gridded rainfall product was based on a pair-wise comparison of the gauge rainfall and gridded datasets. The analysis was performed over the whole Lanckang-Mekong River Basin rather than the two individual sub-basins due to the limited rainfall stations within the sub-basins. Remotely sensed precipitation measurements were extracted and validated at the pixel location of the rain gage stations assuming that the rain gauge observations were the ground truth data. Accuracy was assessed by computing a number of evaluation coefficients including:

1. Mean absolute error (MAE):

$$MAE = \frac{\sum |O_i - \hat{P}_i|}{\mathrm{N}}$$

2. Coefficient of Determination:

$$R^2 = \left\{ \frac{\sum_1^n (O_i - O_{avg})(S_i - S_{avg})}{\left[\sum_1^n \left(O_i - O_{avg} \right)^2 \sum_1^n \left(O_i - O_{avg} \right)^2 \right]^{1/2}} \right\}^2$$

R^2 is a measure of the collinearity between the measured and observed data. R^2 ranges between 0 and 1 and as values approach 1, results become more statistically sound (Legates and McCabe, 1999). MAE is used to measure how close predicted estimates are to the observed values with smaller values of MAE indicating better performance. A full assessment of the climatic predictions is shown in **Figure 7.1-2** and ANNEX 3-4. Overall, the remotely sensed estimated rainfall (CHIRPS and TRMM) showed a relatively strong correlation with the rain gage measurements (R^2 = 0.68, p-value < 0.001) and (R^2= 0.75, p-value < 0.001) respectively. Statistical analysis of the correlation of the TRMM and CHIRPS rainfall products indicated there was a statistical difference between both products at the 0.05 significance level. As a result, it was decided to use the TRMM data as the preferred rainfall product for the region due to the higher R^2. The long term (19-year) rainfall statistics of the basin based on the selected gridded rainfall product was compared to individual rainfall years of record (2009/2010 and 2012/2013).

Figure 7.1-2 | Remote Sensing versus Rain gage accuracy assessments in the Lancang-Mekong River Basin

Streamflow data consisted of daily discharge data at the Chiang Saen and Luang Prabang stations. Streamflow data for each station available from 1985-2016 was used in this study. Initial screening of the observed streamflow data revealed inconsistencies in dry season flow values measured in Chiang Saen, while greater consistencies were observed at downstream stations when compared to literature reported values. Our data quality control included comparing the discharge data with the rating curves used. However, there was very little rating curve information for the data before 2008. The two streamflow station locations were used in conjunction with a digital elevation model downloaded from the hydroSHEDS data portal to delineate the sub-basin boundaries at Chiang Saen and Luang Prabang (**Figure 7.1-1**).

Daily global potential evapotranspiration (PET) was obtained from the USGS FEWS NET Data Portal (https://earlywarning.usgs.gov/fews). The FEWS-daily PET data which is available from 2001 to present is based on the Penman-Monteith equation using climatic data from the National Oceanic and Atmospheric Administration (NOAA) Global Data Assimilation System (GDAS). The sub-basin boundaries were used to derive mean areal values for each of the gridded products (TRMM, CHIRPS and FEWS-PET).

7.2 Hydrological Model Setup

For this project we used the GR suite of lumped hydrologic model as implemented in the airGR package (Coron et al., 2017) of the R statistical program. There are 6 GR models in the airGR package, which run on hourly to annual time scales with 1-6 optimization parameters. We tested two daily time step models: the 4-parameter GR4J model and the 6 parameter GR6J model which includes a snow module. The snow module however proved not to increase the performance of the model simulations so the GR4J was retained for its parsimony and robustness. GR4J is a lumped rainfall-runoff model that converts daily areal rainfall and PET into simulated daily streamflow. Model parameters include two storage parameters, groundwater exchange coefficient and a unit hydrograph time parameter. A brief description of the model is presented in Annex 4 and full details are in Perrin, Michel, & Andréassian, (2003) and Coron, Thirel, Delaigue, Perrin, & Andréassian, (2017). Model calibration was performed by optimizing the 4 model parameters iteratively for the flow time series recorded in Chiang Saen and Luang Prabang. Since the focus of this project was to evaluate dam impact on dry season flow, model performance was evaluated by computing the Nash-Sutcliffe criterion on a logarithm transformed flow (NSElnQ). NSElnQ is an intermediate indicator with greater emphasis on low flows but still sensitive to high flows (Pushpalatha et al., 2012). The model was calibrated for the period 1998-2008 across each sub-basin. The calibrated model parameters were then used to estimate streamflow from 2009 through 2016 assuming no hydrological power development. Observed streamflow (with dam development effects) were then compared to simulated streamflow to analyze the effects of dams by computing the percent deviation between the two datasets:

$$D = 100 * \frac{Q_{obs} - Q_{sim}}{Q_{sim}}$$

where Qsim is the simulated daily flow assumed under natural conditions and Qobs is the observed daily flows under dam operations.

7.3 Results and Discussion

7.3.1 Rainfall

Long term (19 year) rainfall analysis in the basin shows that for both the 2009/2010 and 2012/2013 dry seasons, the basin experienced low rainfall over most of the period with most monthly values below the 19 year median (**Figure 7.3-1**). The November 2012 and January 2012 rainfall were above the long term median whereas both the 2009/2010 and 2012/2013 rainfall were above the long term median during the months of April and May.

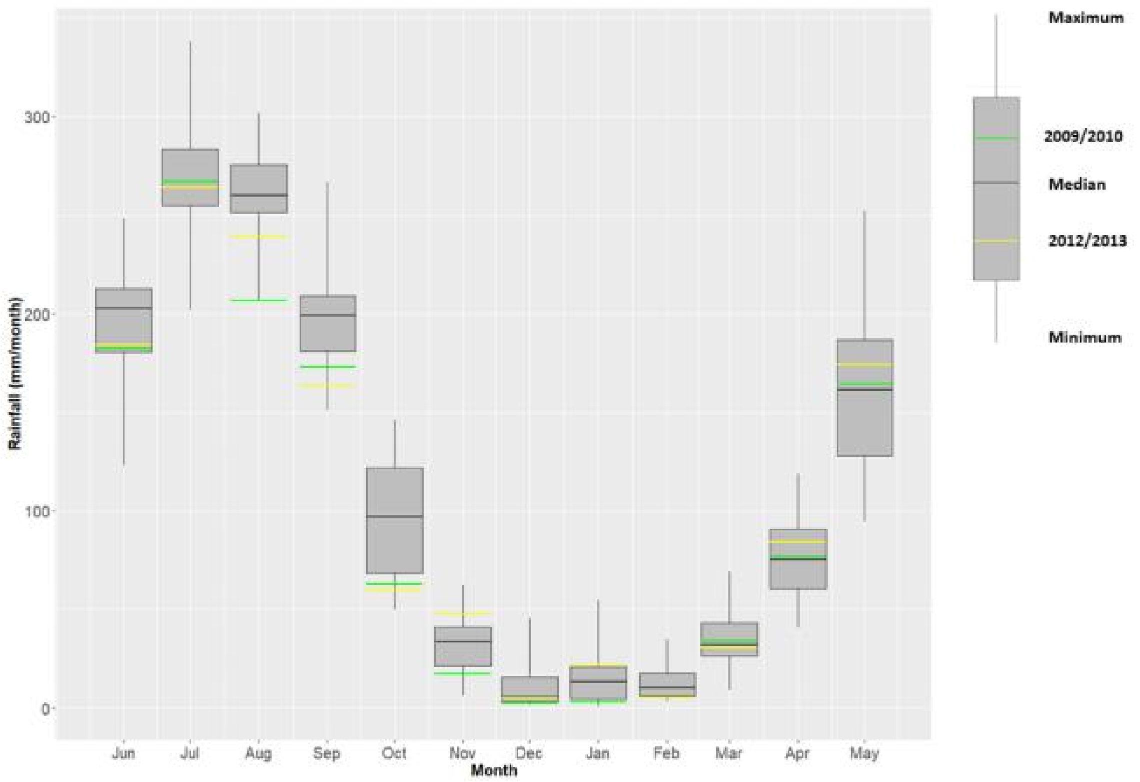


Figure 7.3-1 | Long term (1998-2016) monthly rainfall distribution in the Lancang-Mekong River Basin compared to rainfall for hydrologic years 2009/2010 and 2012/2013

7.3.2 Observed Flows

The analysis of observed daily discharge data showed considerable changes for the pre-dam development (before 2009) when compared to post dam development at both Chiang Saen and Luang Prabang (**Figure 7.3-2**).

Chiang Saen

In 2009/2010 dry season, flows were below or at average flows of the pre-dam period (**Figure 7.3-2A**). Flows were below average from October through early December 2010 when there were a few days of higher than average flows. During the first half of January 2010, flows were below average but rapidly increased to be above average for the rest of the month. Flows remained low from February 2010- April 2010 and even recorded new lows for several days in February. The 2012/2013 dry season flows were lower than average from October-November 2012 and then remained higher than average for the rest of the period (December 2012– May 2013). The 2015/2016 dry season showed extreme lows in October 2015 and higher flows with extreme highs in January 2016, February 2016 and from March through May 2016.

Luang Prabang

At the Luang Prabang station, a similar pattern of flows was observed although at much lower peaks (**Figure 7.3-2B**). The discharges for the 2009/2010 dry seasons was mainly average with almost constant runoff of about 1250 m^3/s for an extended period (January – May). Only a few days did flows occur slightly above or below average whiles the early part of the dry season (October-December 2010) witnessed a gradual decrease of flows which were characteristically below average. Discharge during 2012/2013 was similar to the 2009/2010 dry season flows, a gradual decrease in flows from October 2012 through November 2012 which were below average and a relatively constant but slightly higher than average flow from December 2012 through May 2013. Extreme highs were observed in February, March and April 2013. Flows observed in 2015/2016 were higher than average in January and February 2016, and throughout March-May whiles the months of October–November 2015 experienced record new low discharges.

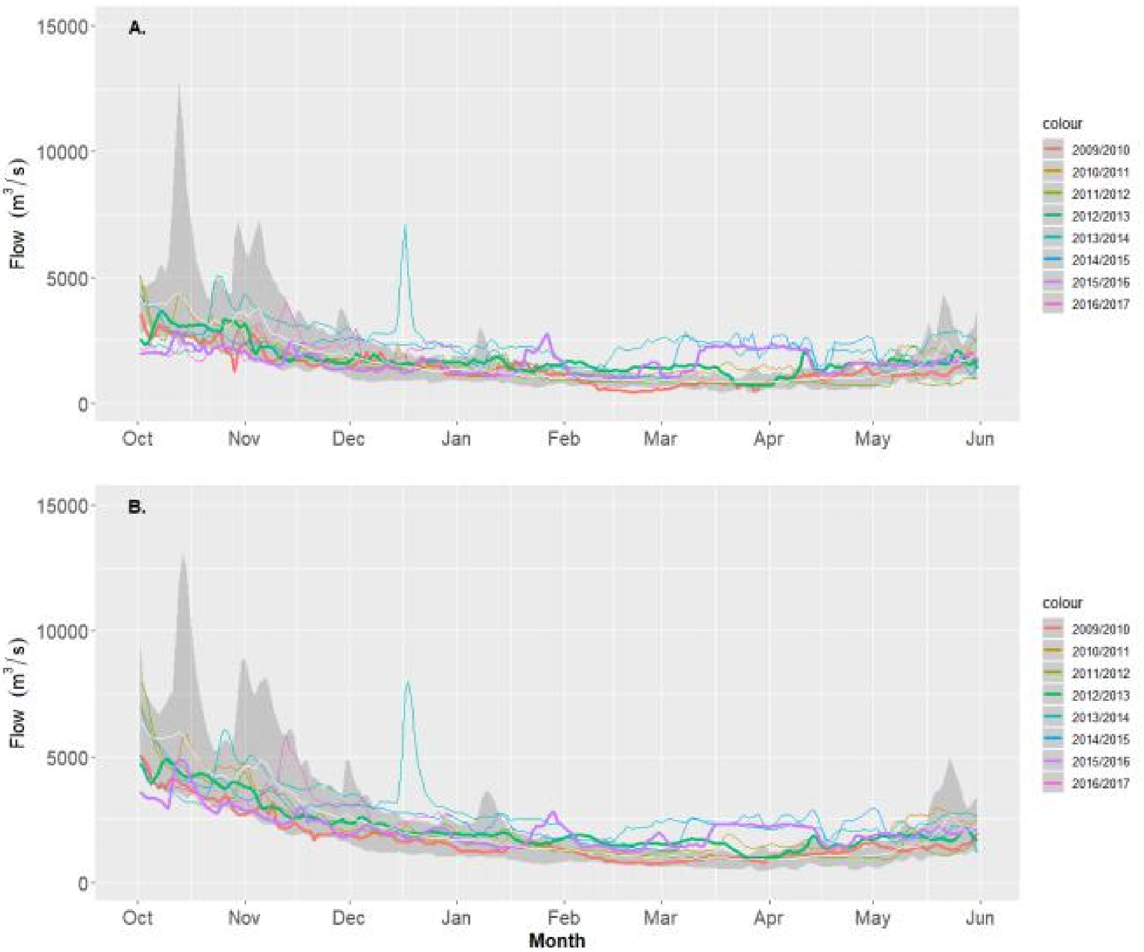


Figure 7.3-2 | Observed streamflow from pre-dam period 1998-2008 (minimum and maximum in grey) compared to post-dam period 2009-2016 for A. Chiang Saen and B. Luang Prabang

7.3.3 Model Calibration and Validation Performance

Model calibration and validation results are shown in **Figure 7.3-3** and **Figure 7.3-4** for Chiang Saen and Luang Prabang stations. Although simulated flow was close to observed values, the time series plots showed some periods of over-prediction and under-prediction at both stations. In particular, the peaks of September 2000 and 2001 of both stations and the peak of October 2006 at Luang Prabang were over predicted. Although there were periods of over prediction, the model seemed to perform better in simulating low flows than high flows. The better performance of GR4J in simulating low flow conditions was not entirely surprising since the model was setup to optimize calibration focusing on low flows (NSElnQ). Nonetheless the GR4J model performed well overall with overall NSElnQ of 0.84 and 87 during calibration and validation at Chiang Saen and NSElnQ of 0.92 during both calibration and validation phases at Luang Prabang. This was confirmed by both the time series plots, which showed consistent seasonal trends with the observed data, and the scatter plots (**Figure 7.3-3** and **Figure 7.3-4**).

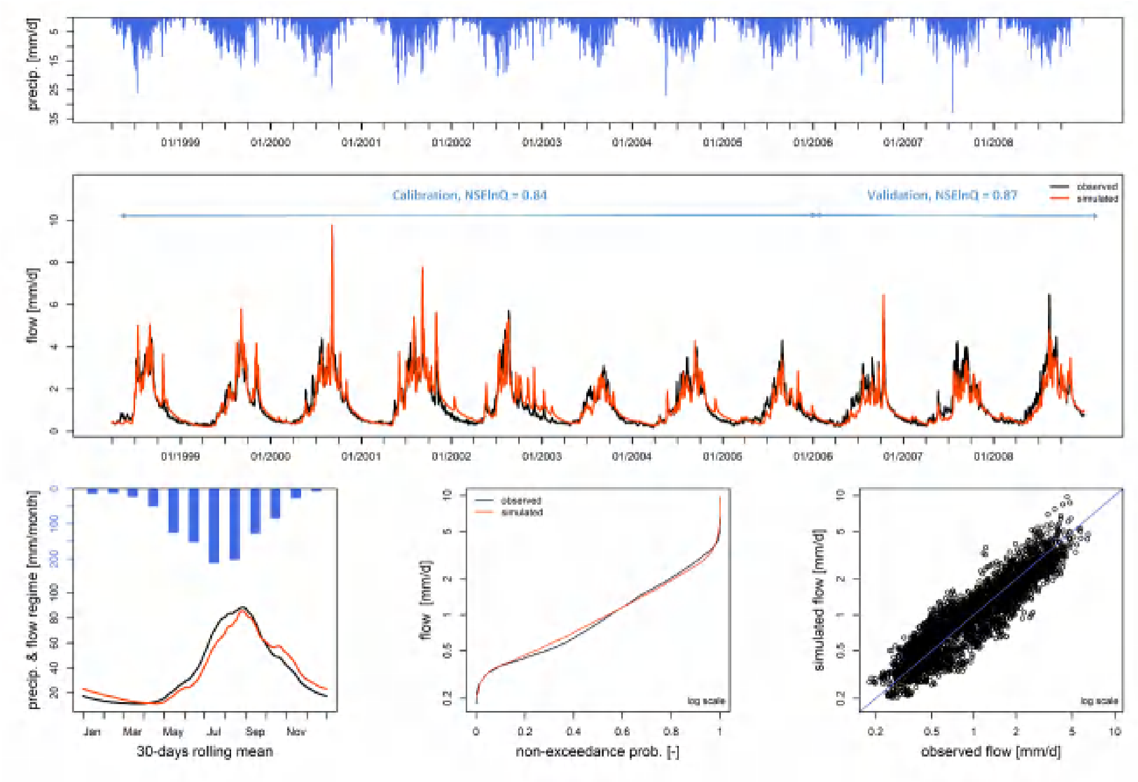


Figure 7.3-3 | GR4J Model simulated versus observed calibration graphs for Chiang Saen station

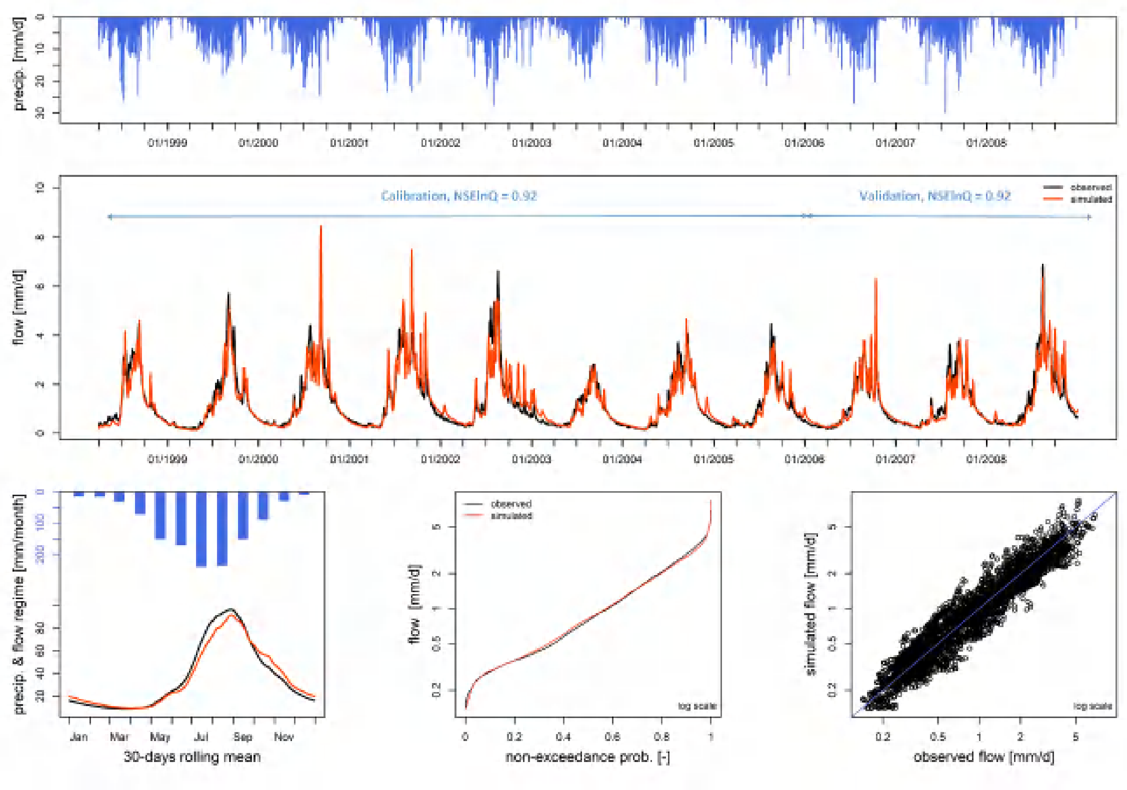


Figure 7.3-4 | GR4J Model simulated versus observed calibration graphs for Luang Prabang Stations

7.3.4 Comparison of Observed and Simulated Flows

The results of the observed flow analysis described above indicated a marked difference between pre-dam development flows and post-dam development flows. To identify the cause of the differences, hydrological effect of climatic variability were isolated from others by comparing simulated model results under natural conditions with the observed post-dam development flows. Consequently, the simulated flows represent the expected flows under the pre-dam development conditions whereas the observed flows represent currently observed flows post-dam development. By comparing the simulated (expected) flows with the observed flows, two sources of streamflow response were identified: 1. any deviations between the simulated and observed flows was attributed to hydropower operation, 2. any agreement between simulated and observed flows was attributed to streamflow response to climate variability (rainfall). **Figure 7.3-5** shows the seasonal simulated and observed flows at Chiang Saen. The 2009-2010, 2012-2013 and 2015-2016 dry seasons all showed large deviations between the observed and simulated flows (**Table 7.3-1**). Except for the events of the last few days of October and November 2009 and February 2010- mid-March 2010, almost all the dry season flows were higher than simulated flows.

Table 7.3-1 | Summary statistics in percent deviation of simulated dry season streamflow under natural conditions versus observed dry season streamflows (with hydropower dams). A positive indicates increase in streamflow while a negative value indicates a reduction in dry season flow

Station / Statistic	Dry Season Period (October- May) 2009/2010	2012/2013	2015/2016
Chiang Sean			
Average Dry Season Increase (%)	44	97	70
Maximum daily dry season flow Increase (%)	274	343	268
Maximum daily dry season flow Decrease (%)	-37	-3	-50
Luang Prabang			
Average Dry Season Increase (%)	63	71	82
Maximum daily dry season flow Increase (%)	265	277	302
Maximum daily dry season flow Decrease (%)	-4	-1	-46

The dry season of 2012/2013 showed similar characteristics as the 2009/2010 dry season. A large deviation from simulated natural flows. Overall, dry season flows have increased on average, 44-97% for the periods considered with the greatest increase occurring during the 2012/2013 dry season (**Table 7.3-1**). For the 2013/2014 period a rapid increase in flows from December 13, 2013 was observed to peak around December 17, 2013. This pattern was also noticed in the simulated natural flows with relatively similar magnitude.

Simulated and observed flows were not much different at the Luang Prabang station (Figure 7.3-6). The 2009/2010 dry season flows showed relatively good temporal and seasonal agreements between observed and simulated natural flows during both the wet (June-October 2009) and dry seasons. Observed dry season flows and simulated natural flows during 2012/2013 were similar to the 2009/2010 flows, with concurrent peaks and recessions for the most part except for small peaks in January 2013 and April 2013. However, observed flows were consistently higher than simulated natural flows throughout most of the dry season. In fact except for two days in November 2012 when simulated flows exceeded observed flows (by about 1%), observed flows remained higher than the simulated. The rapid increase in to peak flows from December 13-17 observed at Chiang Sean was also observed at Luang Prabang, although there seemed to be a lag of about 1 day in the timing of flows. The concurrent flow peaks of observed and simulated flows in December 2010, 2013, November 2016 all suggest that these events were primarily due to rainfall events.

Simulated and observed flows followed a relatively similar pattern from October 2015 through mid-February 2016 (with the exception of some deviation in November 2015 and December 2015). However, observed streamflows exceeded simulated for a large duration of the dry season (the first and last weeks of October 2015, early November and December 2015, and from mid-December 2015 throughout remainder of the dry season). At the Luang Prabang station, dry season flows increased 63-82% with the largest variability in streamflow changes occurring during the 2015/2016 dry season period (**Table 7.3-1**).

Figure 7.3-5 | Observed versus simulated flows at Chiang Saen for hydrological years 2009-2010, 2012-2013 and 2015-2016. Simulated flows represent flows under pre-dam conditions and observed flows represent flows under post-dam conditions. Differences between both curves were attributed to hydropower operations while congruence was attributed to climatic variability.

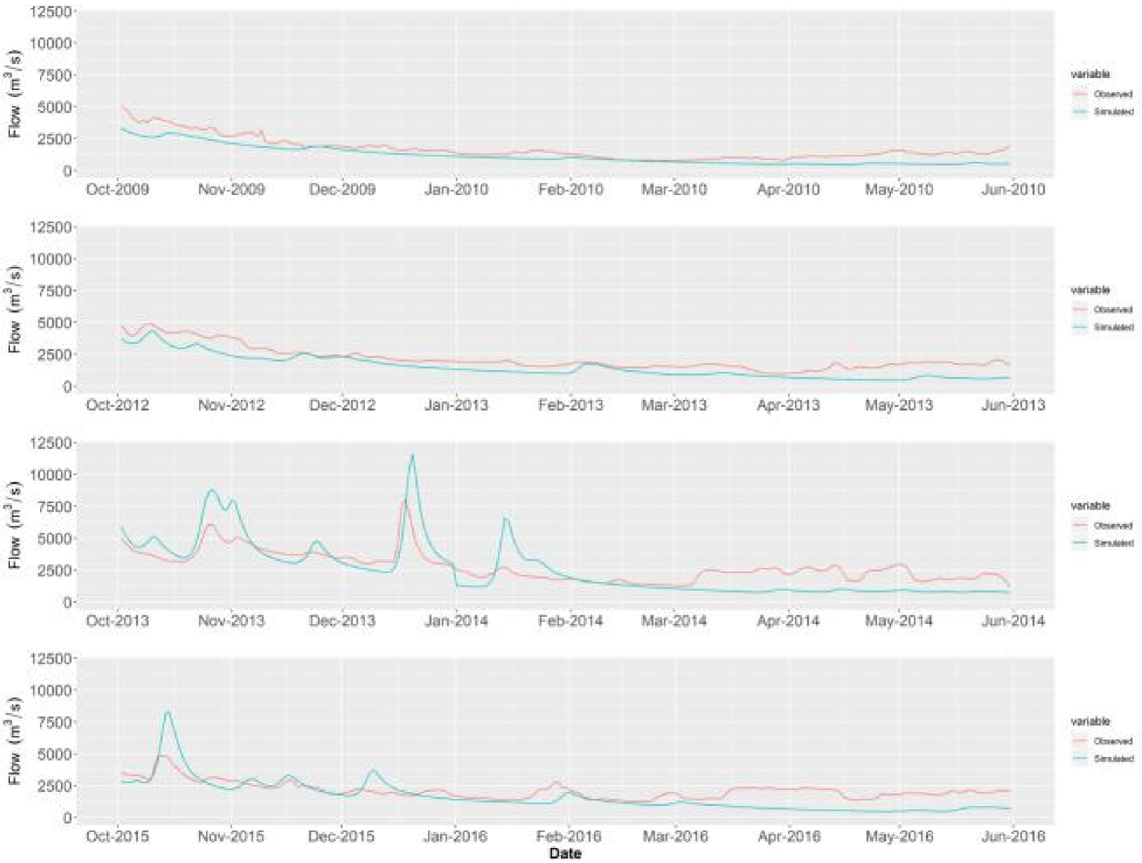


Figure 7.3-6 | Observed versus simulated flows at Luang Prabang for hydrological years 2009-2010, 2012-2013 and 2015-2016. Simulated flows represent flows under pre-dam conditions and observed flows represent flows under post-dam conditions. Differences between both curves were attributed to hydropower operations while congruence was attributed to climatic variability.

7.3.5 Discussion

In this study, we used hydrologic modeling to quantify hydrological impacts of the Lancang hydropower cascade on downstream extreme events. The use of remote sensing data, in particular satellite rainfall data enabled us to derive hydrologic response to streamflow over the entire Lancang- Mekong Basin. This highlights the advantages in using high spatial and temporal satellite based earth observation measurements to derive consistent and spatially variable hydrological model inputs in data scarce regions such as the Upper Mekong Basin, where insitu data is scarce. Analysis of the rainfall distribution in the basin shows that both the 2009/2010 and 2012/2013 dry seasons exhibited extreme dry patterns as most of the data fell beyond the typical values. This is in agreement with previously reported extreme drought conditions in the basin (MRC, 2015, 2010b). At Chiang Saen observed streamflows exceeded simulated streamflows considerably for each of the dry seasons (44% in 2009/2010, 97% in 2012/2013 and 70% in 2015/2016) suggesting that these changes may be due to hydropower operation. The gradual rise and fall in the hydrograph during the last few days of November 2009 in observed streamflow was replicated in the simulated flows (although more pronounced), indicating these events may at least be partly due to rainfall. Rainfall events around mid-November 2012 is probably the cause of the corresponding peaks in the simulated and observed flows during that period. Prior hydrological assessments of hydropower impacts in the Lancang-Mekong suggest a 60-92% increase in dry season flows at Chiang Saen (Hoanh et al., 2010; Lauri et al., 2012; Räsänen et al., 2017, 2012) during the months of December-May. Our results for the same period indicates a 49-116% increase in dry season flows which is at the extreme range of prior research. One reason for the higher variability in our study is that our study included different years of study and also an update of new dams that had been constructed since the reporting of previous research (**Table 4.2-1**). At Luang Prabang, there was a noticeable increase in dry season flows with higher average dry season increases during the 2009/2019 and 2015/2016 period compared to Chiang Saen. Our assessment of hydropower impacts at Luang Prabang show a 75-109% increase which is higher than the Hoanh et al., (2010) reported increase of 50% for the period December to May of the dry season.

At both Chiang Saen and Luang Prabang, concurrent flow peaks of observed and simulated flows during December 13-17, 2013 suggests that this may be due to rainfall rather than hydropower operation. A visual examination of the daily rainfall maps during the period further confirmed that these high flows were mainly due to localized rainfall.

7.4 Model Limitations and Potential Improvements

The GR4J model was used to simulate streamflow under natural conditions and compared with observed streamflow with dam effects. Although model calibration results indicated that the model performed well overall, one source of uncertainty in this study is the relatively better performance during low flow conditions when compared to high flow. This could be partially due to the GR4J model structure used in simulating the flows. The model was calibrated by computing the Nash-Sutcliffe efficiency criteria on a log-transformed flows. This indicator was selected to optimize the prediction of low flows since this project focused on the dry season flows. Therefore, a reduced performance in the model during the high flow season is not entirely surprising. Our approach in deviation assessment did not account for model error. As a result, despite the relatively good model calibration performance, some of observed difference between the simulated and observed flows may be attributed to model simulation error and not solely hydropower operation.

Other sources of uncertainties include the observed streamflow data and the rainfall data used in simulating streamflow. It is well acknowledged that uncertainty is inherent in measured data used to calibrate and validate hydrologic models (Di Baldassarre and Montanari, 2009; Harmel et al., 2006; R. D. Harmel et al., 2010). The observed streamflow data were generated from rating curves. Although we performed a quality check on the data, a lack of rating curve information prior to 2008 posed a great challenge. We selected the TRMM rainfall data based on its better performance compared to the CHIRPS data set (R^2 of 0.75 versus 0.67). However other region specific datasets such as the APHRODITE rainfall product have been shown to have higher degrees of accuracy for the region (Tan et al., 2017; Thom et al., 2017). We were unable to utilize the APHRODITE data in this study because a lack of data for our period of interest.

7.5 Analysis of the flash flood event in December 2013

Between the 13 and 15 December 2013, a significant intense rainfall event were recorded downstream of the Jinghong reservoir (248.5 mm at Guanlei station). This series of major rainfall events resulted in a series of unusually high flows. There were suspicions that the flash flood was caused by releases from the Lancang cascade reservoirs[25]. A hydrological assessment of such extreme events would help improve the understanding of the regional floods and help better prepare in downstream countries to reduce damages.

The flash flood analysis in this section is based on the in-situ gauged observation and the satellite rainfall products. The Chapter encompasses the overview of rainfall over the LMB in December 2013, influence on water level and flow propagation along the Mekong mainstream.

7.5.1 Rainfall over the Lower Mekong Basin in December 2013

Rainfall conditions over the Lower Mekong Basin (LMB) have been observed at about 119 ground stations in the basin. The daily collected rainfall data were aggregated to generate daily rainfall distribution for 14 and 16 December 2013 as illustrated in **Figure 7.5-1** below. Spatial presentation of rainfall on these 2 days indicate intensive rainfall prevailed over the upper part of LMB at Chiang Saen and its downstream areas as well as northern Laos. This is somehow consistent with the Satellite Rainfall Estimate (SRE) (a product used by the RFMMC) and Tropical Rainfall Measuring Mission (TRMM) where rainfall are found active in the connection zone between the UMB and LMB as shown in Figure 7.5-2 and Figure 7.5-3, respectively.

[25] Financial Times: China silent on damaging Mekong floods, Pilita Clark. Accessed on 18 July 2014, http://video.ft.com/3682662151001/China-silent-on-damaging-Mekong-floods/World.

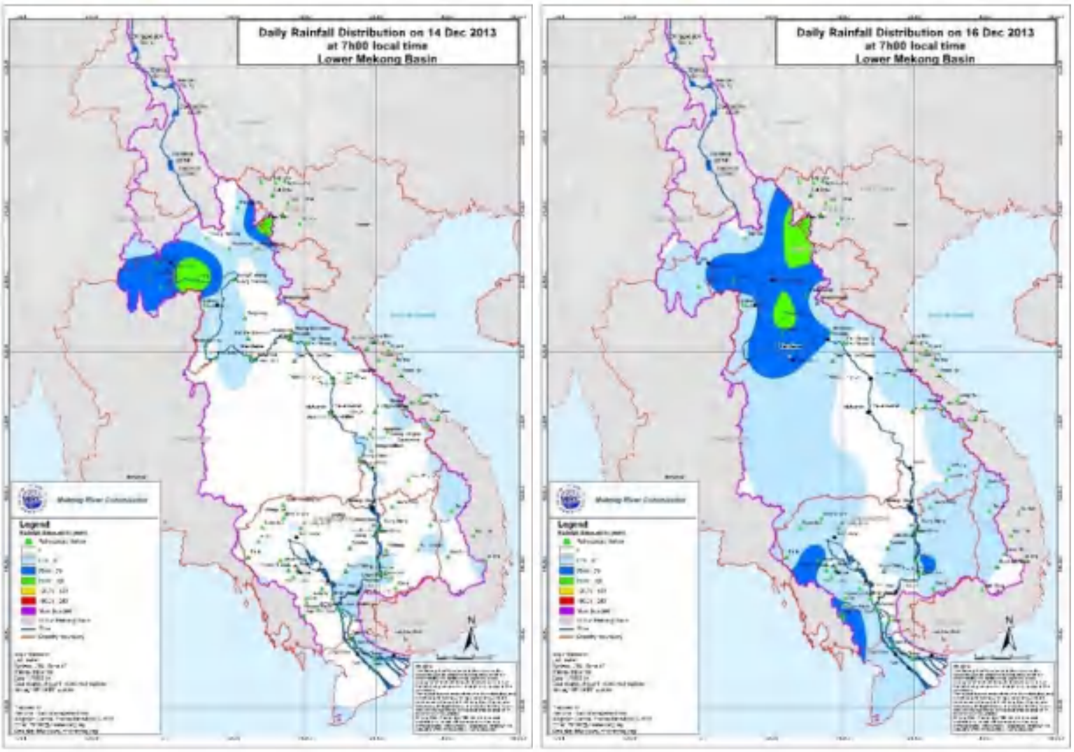


Figure 7.5-1 | Accumulated Daily Rainfall on 14 and 16 December 2013, generated from 119 rainfall stations in the Lower Mekong Basin. Amount of rainfall presents in mm.

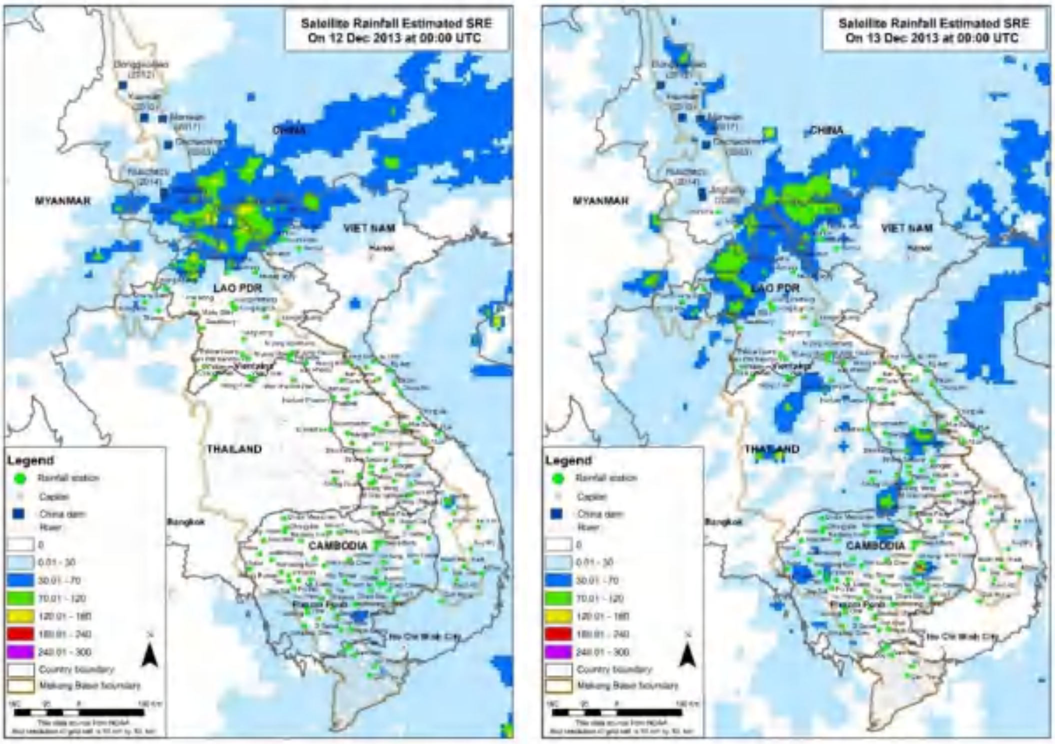


Figure 7.5-2 | 24-hr Satellite Rainfall Estimates (SRE) on 12 and 13 December 2013

The Satellite Rainfall Estimate (SRE) is obtained from NOAA and is a grid-based product of 24 hour rainfalls derived from satellite estimates of the cloud top temperatures. The data is calibrated by NOAA to a limited number of ground truth observations obtained through the WMO's GTS.

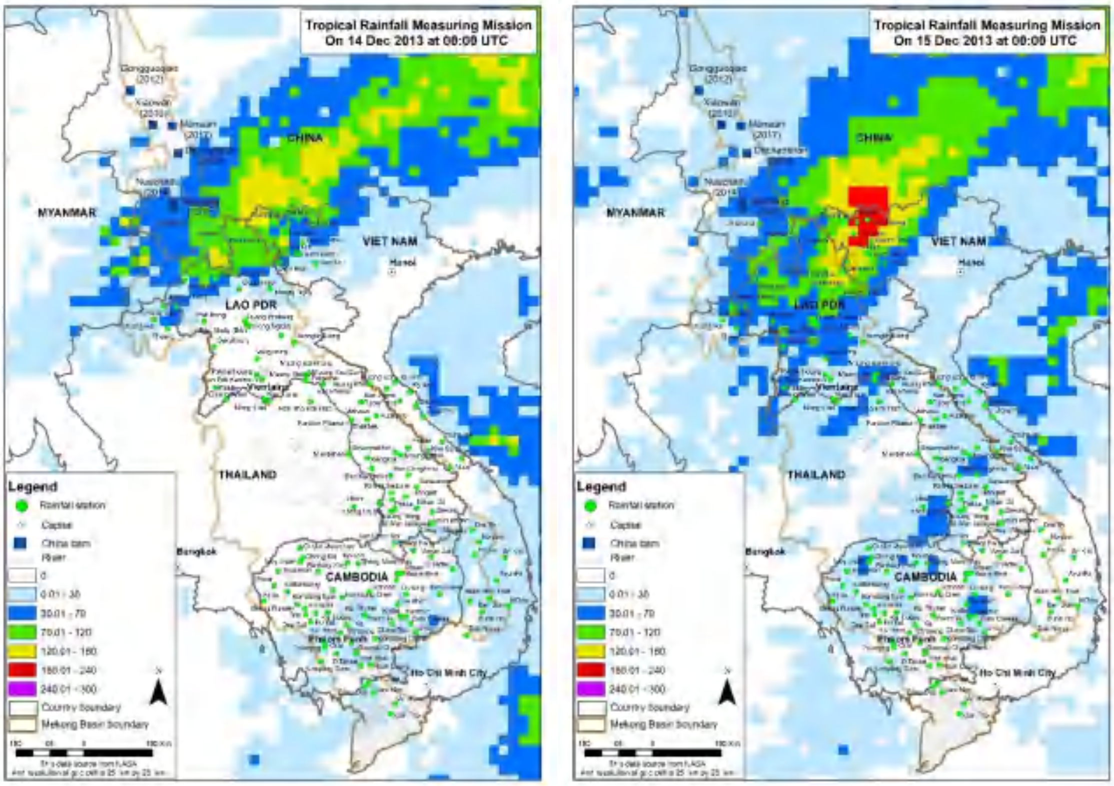


Figure 7.5-3 | 24-hr Tropical Rainfall Measuring Mission (TRMM) rainfall on 14 and 15 December 2013

The Tropical Rainfall Measuring Mission (TRMM), a joint mission of NASA and the Japan Aerospace Exploration Agency, was launched in 1997 to study rainfall for weather and climate research. TRMM consists of a closely knit combination of (i) a passive microwave radiometer TRMM Microwave Imager (TMI), (ii) a precipitation Radar (PR) and (iii) A visible/infrared (VIS/TIR) radiometer. TRMM officially ended on April 15, 2015 after the spacecraft depleted its fuel reserves. The multi-satellite 3B42/TMPA product will continue to be produced through mid-2019. TRMM datasets have been collected and used for the MRC-flood forecasting system.*

The daily rainfall data at 12 typical meteorological stations in the Lancang Basin in December 2013 collected by the Chinese side as provided in Annex 2 reveals similar situation compared with the information derived in the upper part of LMB. In China, the highest amount of rainfall during this event dropped on 14 December 2013 at all stations. This incident was also apparent at stations in the upper part of LMB where highest rainfall amounts were observed on the same day.

7.5.2 Water levels in China

To ascertain the cause of 2013 flash flood whether it was mainly attributed to abnormal rainfall event not Chinese dam release, an investigation of water levels at two downstream stations in Yunnan during December 2013 was observed as plotted in Figure 7.5-4 and Figure 7.5-5 below.

The water level hydrograph at Jinghong does not show remarkable rise of water level if the Dam had released excessive flow beyond its normal operation. The 0.23 m increase of water level from 13 December to its peak on 14 December is consistent with the rainfall record. Similar to the hydrograph at Guanlei station which is further downstream, close to the triangle of China, Myanmar and Lao PDR, the 3.86 m water level rise was observed between 14 to 16 December. This is also in line with very high 3-day rainfall recorded at this location of 200 mm.

From all information described above, it can be concluded that the cause of the extreme event was attributed to the abnormal high rainfall in the Upper Mekong Basin (or Lancang basin) and northern part of the Lower Mekong Basin. This extreme event at upstream locations of Mekong mainstream is unique in historically observed records of 1962-2018.

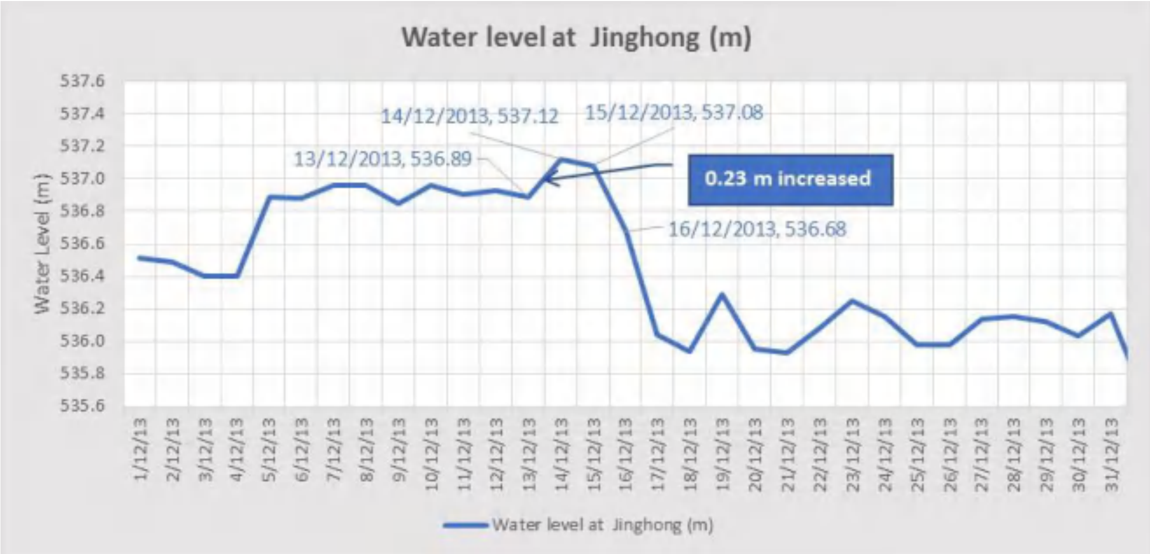


Figure 7.5-4 | Daily water level hydrographs in 2013 of Mekong at Jinghong in December 2013.

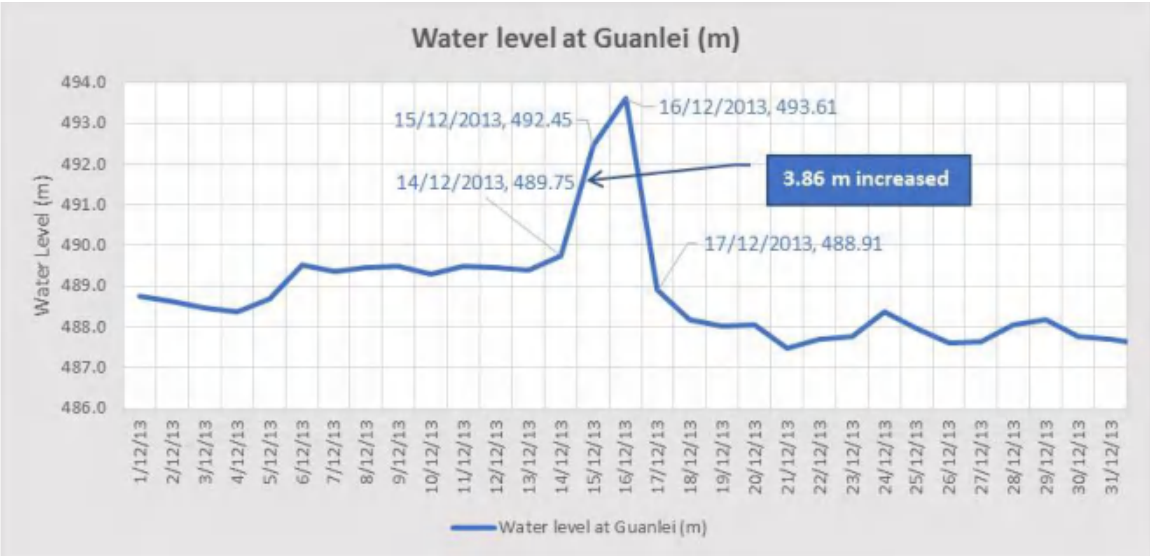


Figure 7.5-5 | Daily water level hydrographs in 2013 of Mekong at Guanlei in December 2013.

7.5.3 Influence on water level

The transient rainfall event in the downstream section of Jinghong station in the Lancang Basin and northern part of the Mekong basin caused a jump in water level recorded at many upstream stations from the mid of December 2013. Examples of water level hydrographs are provided at Chiang Saen, Pakbeng, and Chiang Rai stations as illustrated in **Figure 7.5-6** to **Figure 7.5-8**. Note that Chiang Rai station is a station on Kok river, a major tributary of Mekong in Thailand.

Water levels at these locations were the highest ever recorded in December. Particularly at Pakbeng the maximum daily rainfall record (114 mm) on 14 December 2013 touched the 5-year recurrent interval of annual maximum rainfall, only 23 mm lower than its maximum rainfall in 2013.

At Chiang Rai Station (**Figure 7.5-9**), the peak in December 2013 is regarded as above average flood event and having its recurrent interval between 2 and 5 years of annual flood peak.

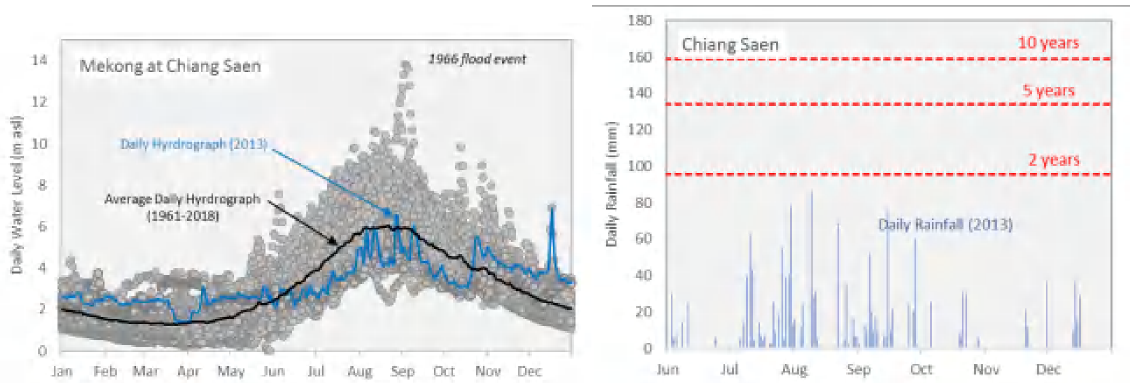


Figure 7.5-6 | Daily water level hydrographs in 2013 of Mekong at Chiang Saen and daily rainfall from June to December 2013.

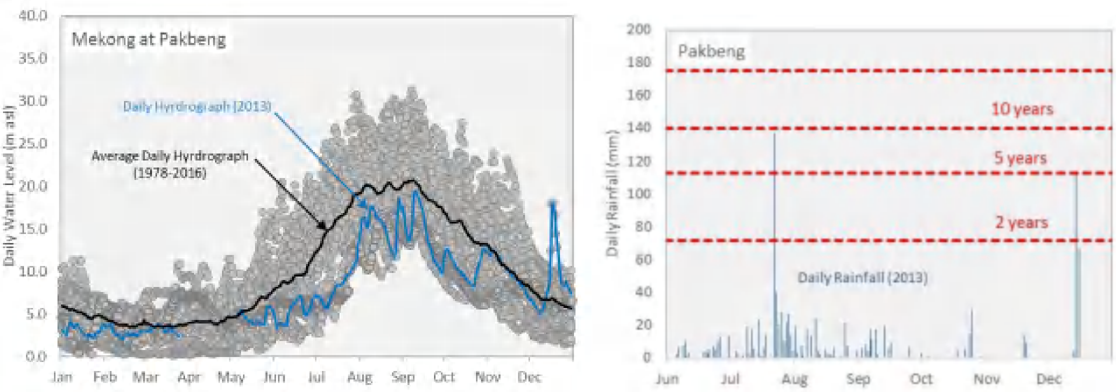


Figure 7.5-7 | Daily water level hydrographs in 2013 of Mekong at Pakbeng and daily rainfall from June to December 2013.

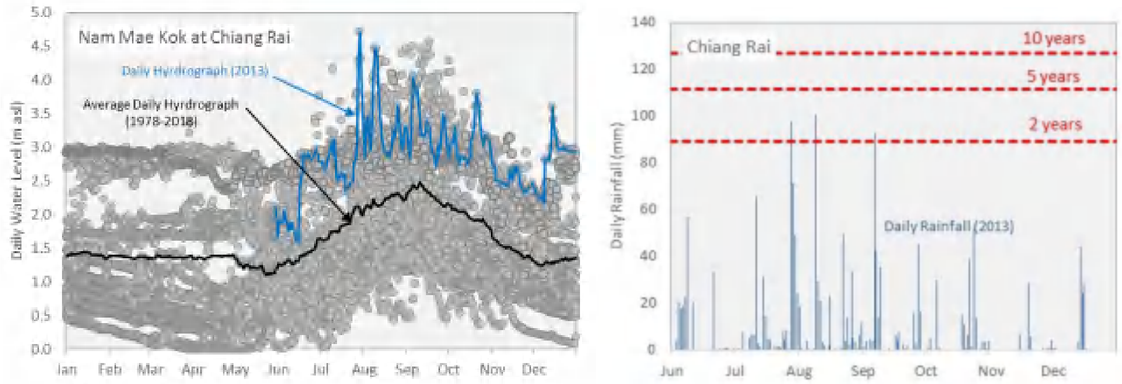


Figure 7.5-8 | Daily water level hydrographs in 2013 of Nam Mae Kok at Chiang Rai and daily rainfall from June to December 2013.

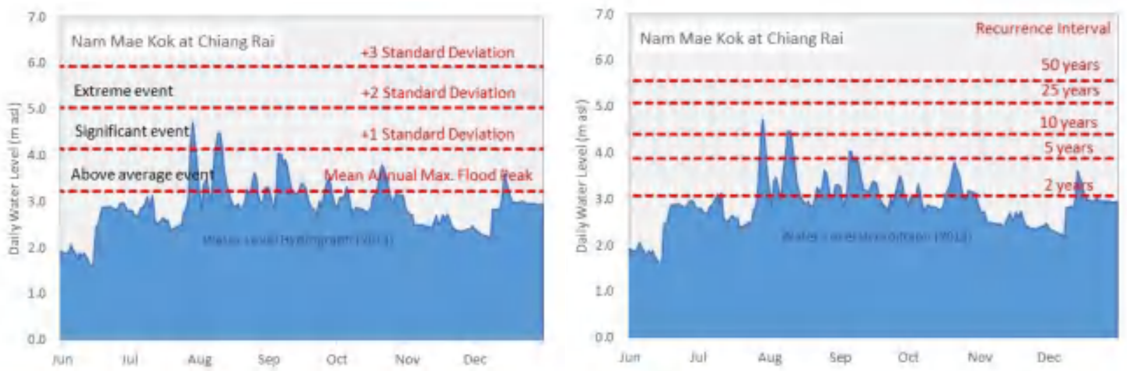


Figure 7.5-9 | Daily water level of Nam Mae Kok at Chiang Rai

7.5.4 Flow propagation along the Mekong mainstream

Flow propagation along the Mekong mainstream was conducted using variation of daily water level and discharge, and sequence of its events. Propagation of the flow pattern along the mainstream was investigated using daily observed water level at 14 selected hydrological stations from Chiang Saen down to Kratie between December 10 to December 31, 2013 as illustrated in Figure 7.5-10. The characteristics of rapid fluctuation of daily observed water level of Mekong river due to abnormal high local rainfall during that period can be observed between Chiang Saen to Kratie though the pattern becomes smoother and less variable at Stung Treng and Kratie.

The extreme event of December 2013 became obviously apparent at Pakbeng rather than Chiang Saen. This is in line with the areas of intensive rainfall which are distributed concentratedly in the Northern Lao PDR, the upper Mekong sub-basins those contribute flow to Pakbeng as discussed in the previous section. A rapid rise of water level at Pakbeng is observed from December 15, 2013 which started from 8.41 m to 18.03 m on December 18, 2013, a 9.62 m increased level.

For other stations this transient rainfall caused total water level rises in Chiang Saen, Luang Prabang, Chiang Khan, Vientiane, Nong Khai, Nakhong Phanom, Tha Khek, Mukdahan, Savannakhet, Khong Chiam, and Pakse for 2.74, 4.88, 3.72, 3.45, 2.72, 2.39, 1.55, 1.92, 1.85, 1.76 and 1.44 m, respectively.

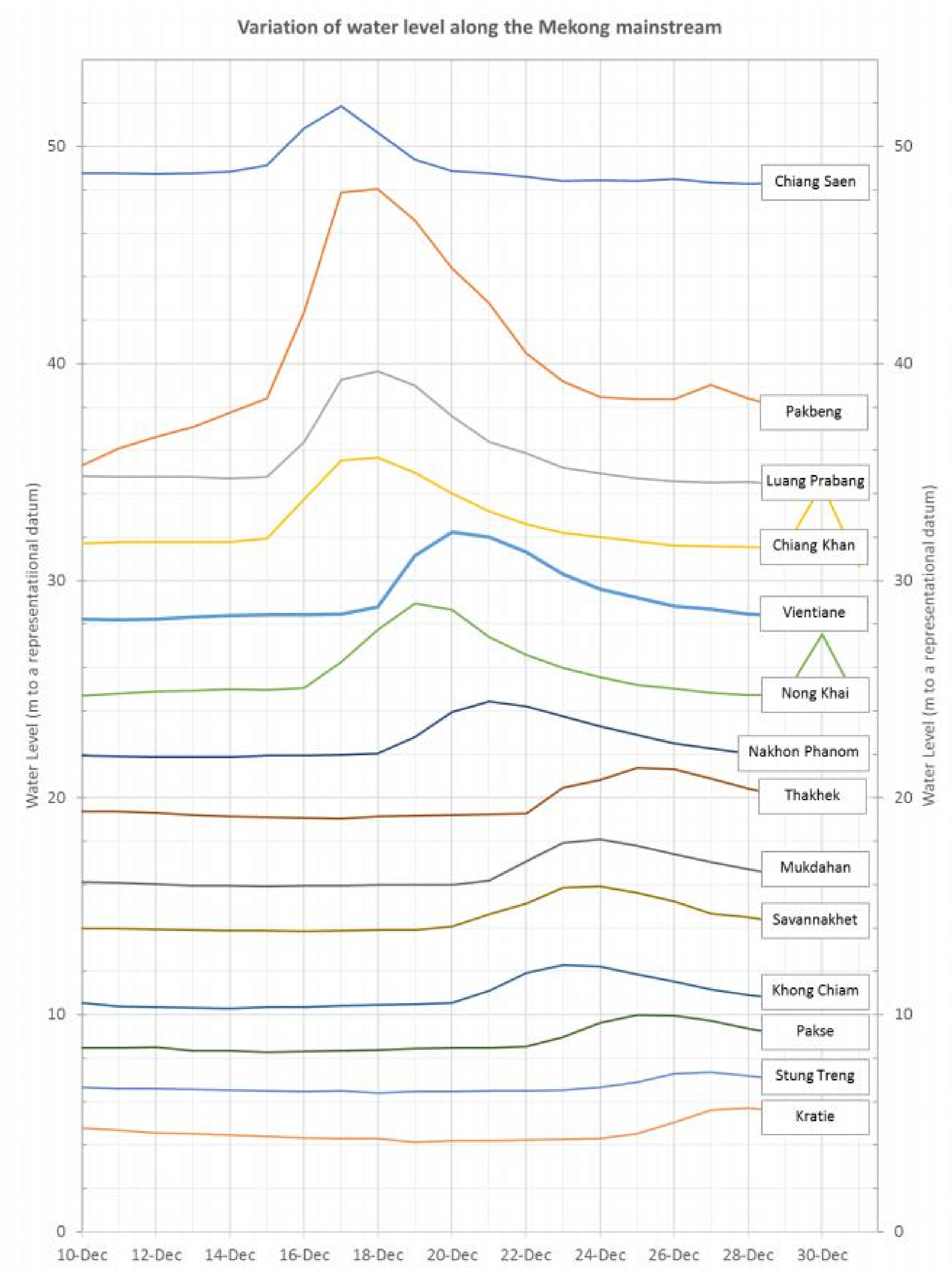


Figure 7.5-10 | Propagation of daily water level along the Mekong mainstream from 10 to 31 December 2013

It is critically important to note that water level is referenced to a representational datum for presentation propose only.

8 Conclusions and Recommendations

To assess the role and impact of the Lancang cascade reservoirs on downstream floods and droughts from the three case studies (1) comparative analysis of the droughts of 2009-2010 and 2012-2013; 2) analysis of extreme drought of 2015-2016; and 3) analysis of the flash flood of December 2013), it is found that 1) the Lancang hydropower cascade has a positive impact on the discharge and water level of the Mekong mainstream in dry season; 2) the emergency water supplement from China during 2015/2016 increased water level and discharge along the Mekong mainstream and decreased salinity intrusion in the Mekong Delta; and 3) the flash flood of December 2013 is primarily attributed to rainfall, not release from the Lancang cascade. The followings are the key findings from the 3 specific scopes of the study.

8.1 Comparative analysis of the droughts of 2009-2010 and 2012-2013

This comparative study compares the two drought events from the meteorological and hydrological perspective, and analyzes the impact of water supplement from Lancang hydropower cascade on the hydrological process of the Mekong River during the dry season of 2012-2013. Conclusions from the analysis are as followings:

1) The inter-annual variation of meteorological drought is not significant. Based on GLDAS monthly rainfall data from 1948 to 2014, SPI was calculated. The results show that the rainfall in Chiang Saen subbasin is characterized by alternation of high and low period, and there is no obvious trend. The rainfall in Mukdahan subbasin and Stung Treng subbasin has a slightly downward trend.

2) The dry season drought in 2009-2010 and 2012-2013 is comparable in the upper reaches of the Lancang-Mekong River Basin. The drought in the lower reaches of the Lancang-Mekong River Basin in 2012-2013 is more severe than that of 2009-2010. The rainfall was less than average in 3 months during the two drought events in the Jinghong subbasin. The drought in 2009-2010 mainly occurred from December to February, and that of 2012-2013 mainly occurred from November to January. The two droughts reached moderate or severe level. The SPI6 results in the Stung Treng subbasin show that the dry season of 2012-2013 mostly belongs to moderate drought, and that of 2009-2010 mostly belongs to light drought.

3) The inter-annual variation of dry season runoff along the Mekong mainstream shows a significant upward trend. The results of SRI6 from 1985 to 2016 show that the discharge of hydrological stations (Chiang Saen, Mukdahan and Stung Treng) along Mekong mainstream shows a significant upward trend. The most severe period of hydrological drought in the upper reaches of the Mekong River was in the late 1990s, and that of the middle and lower reaches was in the late 1980s and early 1990s.

4) In the dry season of 2012-2013, no hydrological drought occurred along the Mekong mainstream. The results of dry season SRI6 show that the SRI values of hydrological stations

along the Mekong mainstream in 2009-2010 ranged from -0.59 to -1.16. That of 2012-2013 ranged from 0.3 to 1.13, indicating that the discharge along Mekong mainstream was slightly or significantly greater than the multi-year average, and there was no hydrological drought occurred. The analysis of hydrological frequency in dry season shows that the drought recurrence period of the minimum daily and monthly discharge of Chiang Saen Station in 2009-2010 is more than 12 years, while the discharge of 2012-2013 dry season has reached the multi-year average.

5) The Lancang hydropower cascade has a positive impact on the discharge and water level of the Mekong mainstream in dry season. Due to the regulation of Lancang hydropower cascade, the monthly discharge of Chiang Saen station in dry season of 2012-2013 is higher than the multi-year average, and the water level is 0.46-1.11 meter higher than the historical average; the monthly discharge and water level of other hydrological stations along the Mekong mainstream after January 2013 is higher than the multi-year average. The rise of water level may also be partly due to rainfall happened in downstream sections of Lancang River.

6) The water supplement of Lancang hydropower cascade has increased the water volume of the Mekong mainstream in dry season. In the dry season of 2012-2013, the water volume at Jinghong station was 5.08 billion m^3 more than the multi-year average, and 6.70 billion m^3 more than that of 2009-2010. For the dry season water volume at Chiang Saen station in 2012-2013, it was increased from multi-year average 17.79 billion m^3 to 23.15 billion m^3, with an increase of 5.36 billion m^3, and it was also 5.89 billion m^3 more than that of 2009-2010.

8.2 Analysis of extreme drought of 2015-2016

Recent meteorological and agricultural drought conditions over the Mekong Basin have worsened and triggered China to implement its emergency water supplement from its cascades dams in the Lancang River to the Mekong River by increasing the water discharge from Yunnan’s Jinghong Reservoir. The emergency water supplement was implemented with a ‘three-phase plan’: (1) from 9 March to 10 April 2016, with an average daily discharge of no less than 2,000 m^3/s; (2) from 11 April to 20 April 2016 with discharge of no less than 1,200 m^3/s; and (3) from 21 April to 31 May 2016 with discharge of no less than 1,500 m^3/s. The Mekong River Commission acknowledges this action by China, in which China has also stated that it implemented the water supplement at a challenging time, especially within the context where China itself was also suffering from drought, which had affected its household water supply and agricultural production.

It is found from the Joint Observation and Evaluation of the Emergency Water Supplement from China to the Mekong River that the emergency water supplement from China increased water level and discharge along the Mekong mainstream and contributed in decreasing salinity intrusion in the Mekong Delta. The following are the key findings from this study:

- Reduced rainfall amount and inflow discharge to the Lancang Basin have been observed in the dry season of 2016. Likewise, the Mekong Basin has been experienced by abnormally dry conditions with high temperature and less rainfall. These meteorological and agricultural droughts are strongly believed to be impacted by the super El Niño 2015-2016.
- Monitoring of flow conditions on the mainstream suggests that water level and discharge in the dry season of 2016 at Vientiane/Nong Khai and Stung Treng in December 2015 were few days below the long term minimum of 1960-2009. However, thanks to the emergency water supplement from China, the water level and discharge at most stations along the Mekong mainstream were most of the time above the long term average and even higher than the long term maximum in March and April 2016.
- Total volume released at Jinghong was 12.65 billion m^3: 6.10 billion m^3 from 9 March to 10 April 2016, 1.07 billion m^3 from 11 April to 20 April 2016, and 5.48 billion m^3 from 21 April to 31 May 2016.
- During the period of the emergency water supplement in March and April 2016, the monthly discharges at Jinghong were 1,280 m^3/s and 985 m^3/s respectively, larger than the average of 1960-2009, and 704 m^3/s and 442 m^3/s respectively, higher than the average of 2010-2015.
- The emergency water supplement from China arrived at Chiang Saen on 11 March and increased till 14 March 2016. This pattern reached Luang Prabang on 14 March, Chiang Khan on 17 March, Nong Khai on 19 March, Nakhon Phanom on 22 March, Mukdahan on 23 March, Pakse on 25 March, Stung Treng on 27 March, Kratie on 28 March and Tan Chau on 1 April 2016. Similarly, the emergency water supplement increased water level or discharge along the Mekong mainstream to an overall extent of 0.18-1.53 m or 602-1,010 m^3/s. Equally, the maximum salinity in the Mekong Delta decreased by 15% and 74%, and the minimum salinity decreased by 9% and 78% according to observation stations.
- Monitoring at Chiang Khan suggests that additional water of 300 m^3/s for one day on top of the emergency water supplement from China was detected on 27 March 2016. This additional water arrived at Nong Khai on 28 March, at Nakhon Phanom on 31 March, at Mukdahan on 1 April, at Pakse on 3 April and at Stung Treng on 4 April 2016. Immediately after the peak of the additional water, a drop in discharge of 300 m^3/s was recorded on 31 March 2016.
- Total volume in the dry season of 2016 (December 2015 to May 2016) at Jinghong presented huge portion (40%-89%) of the total volume at different stations along the Mekong mainstream. Additionally, the volume from 10 March to 10 April 2016, which was first period of the emergency water supplement, claimed significant portion, specifically 99% at Chiang Saen, 92% at Nong Khai and 58% at Stung Treng. Similarly, net contribution of the water supplement in term of discharge to total discharge was 47% at Jinghong, 44% at Chiang Saen, 38% at Nong Khai and 22% at Stung Treng. This contribution also alleviated salinity intrusion in the Mekong Delta.

8.3 Analysis of the respective hydrological impacts of climate variability and hydropower operation

This study sought to differentiate the effects of actual hydropower dam operation and climate variability on streamflow for two sub-basins of the Lancang-Mekong basin, namely Chiang Saen and Luang Prabang. We achieved this by comparing observed and simulated discharge data under different conditions and time periods. First, observed discharge prior to 2009 and was compared to observed discharge data after 2009 when dams were in operation. Next, the GR4J model was calibrated to predict daily streamflows for the two stations. The model was calibrated with observed gauge data for the period 1998-2008 when there was minimal hydropower dam operations in the basin. With model calibrated parameters, the model was used to simulate streamflows for the period 2009-2016 assuming no hydropower dam development. Simulated streamflow under “natural” conditions were then compared to observed streamflow for the period 2009-2016 after significant hydropower dam development happened within the basin. The dry seasons of 2009/2010, 2012/2013 and 2015/2016 were evaluated to assess the magnitude and occurrence of hydrological changes within these periods. The following observations can be made:

- Both the Chiang Saen and Luang Prabang stations have experienced significant hydrological change from 2009-2016 compared to 1998-2008.
- There has been increased streamflows during the dry seasons of 2012/2013 and 2015/2016 which can be attributed mainly to hydropower influences.
- The flash flood of December 2013 is attributed to rainfall happened in downstream sections of Lancang River, not the regulation of Lancang hydropower cascade.

Results from this modeling study can be used to better understand the influences of the climate and the Lancang cascade reservoirs on downstream flows.

8.4 Recommendation

Building on the Joint Observation and analysis in 2016, the Joint Research has provided better understanding of the impacts of cascade dams operations on some selected past extreme events and enhanced further collaborative efforts among key institutions and peoples in the Lancang-Mekong countries. Each party had worked together and contributed their professional and sincere effort with warmth, friendliness and respect. This kind of joint study and working mechanism has built a strong foundation for further cooperation between China, Mekong River Commission and its partners.

Based on the results of the Joint Research, the following are recommended:

First, key findings should be disseminated widely to stakeholders and the public which would increase and clarify their perceptions and understanding about the actual impacts of dam operation on some selected past extreme events in public memory. Dissemination channels would be the MRC Regional Stakeholder Forum as well as communication channels of China, LMWRCC and IWMI.

Second, based on the river monitoring and forecasting of the MRCS and with support of the MRCS and LMWRCC, the MRC Joint Committee and the LMC Joint Working Group on Water Resources should convene a special joint meeting as needed on situations of unusual/extreme flood and/or drought and how dam cascade operation could address the issue.

Third, further joint studies are needed to further increase our knowledge base, enhance data and information sharing, improve or establish better coordination mechanisms and formulate specific basin-wide strategies and policies.

9 References

Coron, L., Thirel, G., Delaigue, O., Perrin, C., Andréassian, V., 2017. The suite of lumped GR hydrological models in an R package. Environ. Model. Softw. 94, 166–171. https://doi.org/10.1016/j.envsoft.2017.05.002

Di Baldassarre, G., Montanari, A., 2009. Uncertainty in river discharge observations: A quantitative analysis. Hydrol. Earth Syst. Sci. 13, 913–921. https://doi.org/10.5194/hess-13-913-2009

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 150066. https://doi.org/10.1038/sdata.2015.66

Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L., Arnold, J.G., 2006. Cumulative Uncertainty in Measured Streamflow and Water Quality Data for Small Watersheds. Trans. ASABE 49, 689–701. https://doi.org/10.13031/2013.20488

Hoanh, C.T., Jirayoot, K., Lacomb, G., Srinetr, V., 2010. Impacts of climate change and development on Mekong flow regime. First assessment – 2009, MRC Technical Paper No. 29. Vientiane, Lao PDR. https://doi.org/10.3724/SP.J.1145.2012.00853

McKee, T.B., N.J. Doesken and J. Kleist, 2007. The relationship of drought frequency and duration to time scale. In: Proceedings of the Eighth Conference on Applied Climatology, Anaheim, California. Boston, American Meteorological Society.

Lacombe, G., Douangsavanh, S., Vogel, R.M., McCartney, M., Chemin, Y., Rebelo, L.M., Sotoukee, T., 2014. Multivariate power-law models for streamflow prediction in the Mekong Basin. J. Hydrol. Reg. Stud. 2, 35–48. https://doi.org/10.1016/j.ejrh.2014.08.002

Lauri, H., De Moel, H., Ward, P.J., Räsänen, T.A., Keskinen, M., Kummu, M., 2012. Future changes in Mekong River hydrology: Impact of climate change and reservoir operation on discharge. Hydrol. Earth Syst. Sci. 16, 4603–4619. https://doi.org/10.5194/hess-16-4603-2012

Legates, D.R., McCabe, G.J., 1999. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35, 233–241. https://doi.org/10.1029/1998WR900018

Lyon, S.W., King, K., Polpanich, O. uma, Lacombe, G., 2017. Assessing hydrologic changes across the Lower Mekong Basin. J. Hydrol. Reg. Stud. 12, 303–314. https://doi.org/10.1016/j.ejrh.2017.06.007

MRC, 2018. Field Visit Report - Joint Visit to the Mekong River on 13-14 December 2017, Nakhon Phanom, Thailand

MRC, 2016. Joint Observation and Evaluation of the Emergency Water Supplement from China to the Mekong River

MRC, 2015. Anuual Mekong Flood Report 2012, Mekong River Commission. https://doi.org/10.1017/CBO9781107415324.004

MRC, 2010a. State of the Basin Report 2010, Mekong River Commission. https://doi.org/ISSN 1728:3248

MRC, 2010b. Preliminary report on low water level conditions in the Mekong mainstream. Mekong River Commission. Vientiane, Lao PDR.

Perrin, C., Michel, C., & Andréassian, V. (2003). Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology*, *279*(1–4), 275–289.

Piman, T., & Shrestha, M. (2017). *Case study on sediment in the Mekong River Basin: Current state and future trends*. Bangkok, Thailand.

Pushpalatha, R., Perrin, C., Le, N., Andréassian, V., 2012. A review of efficiency criteria suitable for evaluating low-flow simulations. J. Hydrol. 420–421, 171–182. https://doi.org/10.1016/j.jhydrol.2011.11.055

R. D. Harmel, P. K. Smith, K. W. Migliaccio, 2010. Modifying Goodness-of-Fit Indicators to Incorporate Both Measurement and Model Uncertainty in Model Calibration and Validation. Trans. ASABE 53, 55–63. https://doi.org/10.13031/2013.29502

Räsänen, T.A., Koponen, J., Lauri, H., Kummu, M., 2012. Downstream Hydrological Impacts of Hydropower Development in the Upper Mekong Basin. https://doi.org/10.1007/s11269-012-0087-0

Räsänen, T.A., Someth, P., Lauri, H., Koponen, J., Sarkkula, J., Kummu, M., 2017. Observed river discharge changes due to hydropower operations in the Upper Mekong Basin. J. Hydrol. 545, 28–41. https://doi.org/10.1016/j.jhydrol.2016.12.023

Tan, M.L., Gassman, P.W., Cracknell, A.P., 2017. Assessment of three long-term gridded climate products for hydro-climatic simulations in tropical river basins. Water (Switzerland) 9, 1–24. https://doi.org/10.3390/w9030229

Thom, V.T., Khoi, D.N., Linh, D.Q., 2017. Using gridded rainfall products in simulating streamflow in a tropical catchment - A case study of the Srepok River Catchment, Vietnam. J. Hydrol. Hydromechanics 65, 18–25. https://doi.org/10.1515/johh-2016-0047

WLE, 2017. Dataset on the Dams of the Mekong River Basin.Vientiane, Lao PDR: CGIAR Research Program on Water, Land and Ecosystems - Greater Mekong. [WWW Document]. URL https://wle-mekong.cgiar.org/maps/

Wong, C., 2018. Is Mekong River set to become the new South China Sea for regional disputes? [WWW Document]. South China Morning Post. URL https://www.scmp.com/news/china/diplomacy-defence/article/2126528/mekong-river-set-become-new-south-china-sea-regional (accessed 2.8.19).

WWF, 2013. Ecosystems in the Greater Mekong. Past trends, current status, possible futures.

ANNEX 1 - Team composition

International steering committee

No	Name	Designation/Affiliation
1	Mr. Jeremy Bird Dr. Claudia Sadoff	Director General / International Water Management Institute (2012-2017) Director General / International Water Management Institute (present)
2	Dr Pham Tuan Phan Dr. An Pich Hatda	Chief Executive Officer / Mekong River Commission Secretariat (2016-2018) Chief Executive Officer / Mekong River Commission Secretariat (2019-present)
3	Mr. Zhongping Li	Deputy Director General, Changjiang Water Resources Commission, MWR of China
4	Dr. Yong Zhong	Secretary General / Lancang-Mekong Water Resources Cooperation Center
5	Prof. David Grey	Professor / Oxford University
6	Dr. Fuqiang Tian	Professor / Tsinghua University

International Research team

No	Name	Designation	Role
China Institute of Water Resources and Hydropower Research (IWHR)			
1	Dr. Hui Liu	Senior engineer	Project leader
2	Dr. Baiyinbaoligao	Professor of engineering	Co-project leader
3	Mr. Fengran Xu	Senior engineer	Hydrological analysis
4	Mr. Xuejun Zhang	Senior engineer	Drought assessment
5	Mr. Xiangpeng Mu	Professor of engineering	Statistical analysis
6	Mr. Xiang Li	Senior engineer	Drought assessment
7	Mr. Wei Cui	Professor of engineering	Runoff and discharge analysis
8	Ms. Xiuying Wang	Professor of engineering	Climate analysis
9	Ms. Xingru Chen	Professor of engineering	Climate analysis
10	Ms. Feng Liu	Engineer	Statistical analysis
Lancang-Mekong Water Resources Cooperation Center (LMWRCC)			
11	Dr. Dongsheng Cheng	Professor of engineering	Project leader
12	Dr. Wenhai Zhang	Engineer	hydrological analysis
International Water Management Institute (IWMI)			

No	Name	Designation	Role
13	Dr. Mansoor Leh	Researcher	Co-project leader and Remote sensing and hydrology
14	Dr. Lacombe Guillaume	Senior researcher	Hydrological analysis
Mekong River Commission Secretariat (MRCS)			
15	Dr. Winai Wangpimool	Director, Technical Support Division (2019-present)	Project leader
16	Dr. Janejira Chuthong	Chief Hydrologist	Co-project leader and hydrological analysis
17	Dr. Anoulak Kittikhoun	Chief Strategy and Partnership Officer	Strategic and policy advice
18	Dr. Paradis Someth	Hydrologist (till 2018)	hydrological analysis
19	Dr. Kritsana Kityuttachai	Specialist	Remote sensing and GIS analysis
20	Mr. Rattykone Sayasane	Modeller	Hydrological modelling
Cambodia			
21	H.E. Mr. Long Saravuth	Deputy Secretary General	Team leader
22	Mr. Chheang Hong	National TD Coordinator	Focal point
23	Mr. Meak Chhavannarey	Modeller	Hydrological modelling
24	Representative of Ministry of Water Resources and Meteorology – MOWRAM (Hydrology and River Works Department)	Hydrologist/Modeller	Hydrological analysis
25	Representative of Ministry of Mines and Energy (Hydro-Electricity Department)	Energy Planning Expert	Hydropower infrastructure analysis
Lao PDR			
26	Mr. Phetsamone Khanophet	National TD Coordinator, Lao National Mekong Committee Secretariat	Focal point
27	Mr. Somphone Khamphanh	Assistant TD Coordinator	Specialist 1
28	Representative from Department of energy, policy and planning	Specialist 2	Specialist 2
29	Mr. Prasith Deemaneevong	Senior Hydrologist	Hydrological analysis
Thailand			
30	Ms. Puttikul Tongnuesook	National TD Coordinator, Thai National Mekong Committee Secretariat	Focal Point
31	Mr. Poonsak Wisetsopa	Remote Sensing and GIS Specialist	Remote Sensing and GIS Analysis

No	Name	Designation	Role
32	Representative from Bureau of Research, Development and Hydrology	Hydrologist Specialist, Department of Water Resources (DWR)	Hydrological Analysis
33	Representative from Water Crisis Prevention Center, DWR.	Modeller Specialist, Department of Water Resources (DWR)	Flood and Drought Analysis
34	Representative from related implementing agencies (case-by-case)	Sector Specialist	Hydropower, Infrastructure, Irrigation, Navigation, etc.
Viet Nam			
35	Mr. Nguyen Huy Phuong	National TD Coordinator, Viet Nam National Mekong Committee Secretariat	Focal Point
36	Mr. Nguyen Dinh Dat	Senior Modeller, Viet Nam National Mekong Committee Secretariat	Hydrological modelling
37	Mr. Pham Tuong	Senior Officer, Viet Nam National Mekong Committee Secretariat	Hydrological analysis

ANNEX 2 - Summary Goodness of fit statistics computed when comparing station rainfall data with the CHIPRS gridded rainfall product

Station_ID	MAE	RMSE	NRMSE %	PBIAS %	RSR	rSD	NSE	d	md	cp	R2	bR2	KGE	VE
100303	148.45	251.88	97.9	45.1	0.98	1.26	0.03	0.8	0.68	-0.14	0.48	0.44	0.4	0.26
100401	68.66	103.88	68.2	11.4	0.68	0.91	0.53	0.86	0.71	0.59	0.57	0.51	0.71	0.54
100509	47.34	73.51	59.1	-5.4	0.59	0.86	0.65	0.89	0.76	0.64	0.66	0.55	0.76	0.65
100514	44.64	65.93	61.7	-6	0.62	0.82	0.62	0.88	0.73	0.63	0.62	0.51	0.72	0.63
100516	56.96	83.12	70.1	13.4	0.7	0.89	0.51	0.85	0.71	0.42	0.55	0.49	0.69	0.52
100517	52.94	81.26	64.3	-2.8	0.64	0.8	0.59	0.86	0.73	0.58	0.59	0.47	0.69	0.59
100605	46.74	67.73	58.8	2.9	0.59	0.85	0.65	0.89	0.75	0.66	0.65	0.56	0.75	0.61
100613	47.61	70.23	57.9	0	0.58	0.94	0.66	0.9	0.77	0.65	0.68	0.61	0.81	0.65
100617	46.55	67.81	59	-0.8	0.59	0.87	0.65	0.89	0.75	0.65	0.65	0.56	0.77	0.63
110303	94.36	149.16	41.1	-0.6	0.41	0.92	0.82	0.95	0.83	0.74	0.82	0.73	0.87	0.69
110415	47.81	61.98	61.4	8.8	0.61	0.88	0.62	0.89	0.71	0.64	0.64	0.58	0.75	0.57
110433	94.44	131.88	140.7	83.3	1.41	1.51	-0.99	0.7	0.53	-0.47	0.46	0.32	-0.03	0.04
110434	67.31	92.58	113.5	61.1	1.14	1.24	-0.3	0.74	0.58	0.1	0.46	0.36	0.27	0.24
110450	36.19	46.73	47.9	11	0.48	0.91	0.77	0.93	0.76	0.81	0.78	0.76	0.82	0.67
110508	50.6	71.45	75.3	6.1	0.75	0.89	0.42	0.82	0.64	0.51	0.47	0.41	0.66	0.55
110517	74.89	103.39	88	41.6	0.88	1.02	0.2	0.78	0.6	0.56	0.47	0.45	0.48	0.31
110518	44.93	64.13	86.3	41	0.86	0.99	0.23	0.8	0.64	0.32	0.48	0.46	0.49	0.37
110523	41.19	55.77	69.4	26.1	0.69	1.16	0.51	0.89	0.72	0.6	0.72	0.62	0.66	0.58
110524	42.64	81.49	82.1	2.3	0.82	0.84	0.32	0.77	0.7	0.76	0.37	0.29	0.57	0.6
110525	49.66	68.91	71.2	11.5	0.71	0.88	0.49	0.84	0.67	0.56	0.53	0.48	0.68	0.54
110605	87.86	123.83	86.7	54.8	0.87	1.18	0.22	0.84	0.67	0.44	0.64	0.52	0.39	0.34
110608	66.47	87.31	98.5	56.1	0.99	1.17	0	0.78	0.58	0.43	0.51	0.43	0.35	0.22
120202	56.6	79.49	93.3	45.4	0.93	1.03	0.12	0.78	0.62	0.31	0.46	0.43	0.44	0.35
120303	55.42	81.89	75.5	-1.1	0.75	0.74	0.43	0.78	0.63	0.48	0.43	0.32	0.57	0.5
120313	100.85	140.85	134.2	73.9	1.34	1.53	-0.81	0.72	0.57	-0.4	0.51	0.35	0.05	0.12
120402	61.63	95.92	64.4	-19.2	0.64	0.66	0.58	0.84	0.71	0.56	0.64	0.42	0.56	0.56
120410	45.72	67.49	62.2	23.5	0.62	1.05	0.61	0.9	0.77	0.46	0.71	0.67	0.71	0.59
120417	42.07	65.51	54.4	5.3	0.54	0.87	0.7	0.91	0.79	0.7	0.71	0.64	0.79	0.67
120515	125.25	221.01	103.4	32.9	1.03	0.59	-0.09	0.4	0.45	-0.02	0.06	0.02	0.08	-0.09
120518	50.28	71.55	59.5	19.6	0.6	1.01	0.64	0.91	0.76	0.68	0.71	0.69	0.75	0.61
120602	57.93	80.27	70	24.4	0.7	1.08	0.51	0.88	0.72	0.61	0.66	0.6	0.68	0.57
120712	90.48	133.25	67.7	-9.2	0.68	0.71	0.54	0.83	0.68	0.36	0.55	0.4	0.6	0.55
120805	56.03	84.65	67.2	8.4	0.67	0.98	0.55	0.87	0.73	0.57	0.6	0.56	0.76	0.57
130209	41.86	55.5	64	32.9	0.64	0.96	0.58	0.89	0.72	0.69	0.71	0.66	0.63	0.53
130304	53.54	73.15	114.7	74.7	1.15	1.26	-0.35	0.74	0.58	-0.47	0.49	0.37	0.15	0.12
130307	48.09	68.35	66.2	11.8	0.66	0.89	0.56	0.87	0.7	0.66	0.59	0.52	0.72	0.52
130403	58.03	81.54	58.2	-4	0.58	0.86	0.66	0.89	0.73	0.59	0.66	0.55	0.76	0.6
130604	78.15	116.04	83.6	40.3	0.84	1.33	0.3	0.87	0.71	0.26	0.71	0.56	0.45	0.45
130705	59.76	97.07	43.3	21.2	0.43	1.12	0.81	0.96	0.85	0.75	0.87	0.78	0.75	0.67
130803	80.41	120.71	84.6	29.2	0.85	1.11	0.28	0.82	0.64	0.42	0.51	0.5	0.58	0.38
140105	34.44	48.6	59.5	6	0.59	0.97	0.65	0.9	0.73	0.73	0.67	0.63	0.81	0.6
140201	38.59	56.06	60.1	13.4	0.6	1.02	0.64	0.91	0.75	0.66	0.69	0.69	0.78	0.6
140203	41.22	60.18	70.9	24.9	0.71	1.01	0.5	0.87	0.71	0.59	0.6	0.6	0.67	0.48
140402	57.79	97.7	70.2	-3.1	0.7	0.8	0.5	0.83	0.72	0.4	0.51	0.38	0.65	0.54
140501	58.98	90.82	59.7	24.6	0.6	1.15	0.64	0.92	0.79	0.6	0.77	0.69	0.69	0.58
140502	50.71	78.65	48.7	1.6	0.49	0.97	0.76	0.94	0.81	0.69	0.77	0.72	0.87	0.66
140503	78.69	140.41	39.9	-26.8	0.4	0.71	0.83	0.94	0.85	0.62	0.94	0.67	0.6	0.72
140505	55.83	96.75	40.7	7.5	0.41	0.98	0.83	0.96	0.85	0.79	0.84	0.82	0.89	0.71
140704	52.73	86.08	54.9	-2.3	0.55	0.99	0.7	0.92	0.8	0.63	0.72	0.66	0.85	0.67

Station_ID	MAE	RMSE	NRMSE %	PBIAS %	RSR	rSD	NSE	d	md	cp	R2	bR2	KGE	VE
150107	36.08	54.19	68.7	11.8	0.69	1	0.53	0.87	0.72	0.55	0.59	0.56	0.74	0.54
150201	42.86	65.01	73.2	8.8	0.73	1.02	0.46	0.85	0.71	0.47	0.55	0.51	0.72	0.53
150203	35.97	53.84	63.8	7.4	0.64	0.99	0.59	0.89	0.74	0.63	0.63	0.59	0.78	0.57
150207	40.88	67.43	65.7	-0.6	0.66	0.84	0.57	0.86	0.73	0.67	0.57	0.46	0.71	0.56
150208	40.46	62.41	65.5	-3.4	0.65	0.9	0.57	0.87	0.73	0.6	0.59	0.49	0.74	0.58
150305	40.4	62.13	59.8	16.2	0.6	1.03	0.64	0.91	0.78	0.61	0.7	0.7	0.77	0.59
150306	44.74	67.48	57.9	-3.6	0.58	0.85	0.66	0.89	0.75	0.64	0.67	0.55	0.76	0.6
150405	46.98	73.89	65.7	18.9	0.66	1.02	0.57	0.89	0.75	0.54	0.64	0.63	0.73	0.53
150410	35.29	55.66	40.7	-3.1	0.41	0.92	0.83	0.95	0.84	0.78	0.83	0.76	0.88	0.73
150501	49.74	81.2	53.1	12.4	0.53	1.17	0.72	0.94	0.82	0.62	0.81	0.74	0.77	0.66
150504	51.75	88.85	44	0.9	0.44	0.88	0.81	0.94	0.84	0.78	0.81	0.71	0.84	0.68
150605	83.45	118.37	57.4	-6.5	0.57	1.1	0.67	0.92	0.77	0.59	0.73	0.69	0.81	0.63
150607	89.49	138.13	61.4	-25.5	0.61	0.74	0.62	0.87	0.74	0.48	0.69	0.47	0.6	0.6
160111	49.87	77.3	66.8	-19.3	0.67	0.71	0.55	0.84	0.71	0.51	0.59	0.41	0.59	0.58
160207	52.93	90.22	70.6	-8.3	0.71	0.68	0.5	0.81	0.69	0.55	0.5	0.33	0.56	0.49
160208	32.64	48.06	50.4	6.5	0.5	0.9	0.75	0.93	0.78	0.78	0.75	0.68	0.82	0.63
160303	39.22	63.2	60.3	-2.5	0.6	0.89	0.64	0.89	0.76	0.62	0.64	0.54	0.77	0.6
160401	32.91	55.97	40.8	-5.1	0.41	0.89	0.83	0.95	0.85	0.83	0.84	0.73	0.85	0.73
160402	41.35	61.76	52.5	16.8	0.53	1.09	0.72	0.93	0.8	0.68	0.79	0.74	0.78	0.62
160406	40.66	65.21	47.8	5	0.48	0.92	0.77	0.93	0.81	0.75	0.77	0.7	0.84	0.66
160407	46.17	72.67	52.5	-5.9	0.52	0.9	0.72	0.92	0.79	0.69	0.73	0.62	0.81	0.64
160501	52.52	98.23	61.2	-10.9	0.61	0.78	0.62	0.87	0.78	0.55	0.63	0.46	0.68	0.61
160506	99.83	155.31	97.6	54.2	0.98	1.18	0.04	0.78	0.62	-0.13	0.47	0.43	0.35	0.19
160602	78.83	125.31	95.7	40.6	0.96	1.31	0.08	0.81	0.68	0.05	0.54	0.47	0.42	0.32
160605	66.68	101.74	55.6	2.2	0.56	0.89	0.69	0.91	0.76	0.65	0.69	0.59	0.8	0.56
160704	113.13	211.16	66.8	-12.5	0.67	0.76	0.55	0.84	0.72	0.59	0.56	0.38	0.63	0.52
170104	42.31	62.89	72.1	16.3	0.72	1.12	0.48	0.88	0.73	0.52	0.62	0.6	0.71	0.54
170105	52.02	76.83	75	31.6	0.75	1.24	0.44	0.88	0.73	0.47	0.7	0.59	0.57	0.49
170107	36.32	54.26	55.1	5.1	0.55	1	0.69	0.92	0.78	0.74	0.72	0.69	0.84	0.65
170205	44.02	67.89	54.7	7.1	0.55	0.91	0.7	0.91	0.78	0.64	0.71	0.64	0.81	0.61
170206	36.99	56.13	39.7	0.4	0.4	0.94	0.84	0.96	0.84	0.81	0.84	0.78	0.9	0.72
170302	51.4	82.07	64.8	8	0.65	1.01	0.58	0.89	0.76	0.55	0.63	0.59	0.78	0.58
170304	46.09	71.56	51.6	14.2	0.52	0.99	0.73	0.93	0.8	0.69	0.76	0.75	0.81	0.63
170306	53.41	82.81	51.7	11.3	0.52	1.08	0.73	0.93	0.81	0.68	0.78	0.76	0.82	0.65
170403	60.62	102.95	46.4	-17.5	0.46	0.74	0.78	0.93	0.82	0.7	0.84	0.62	0.68	0.68
170406	65.24	106.12	42	-0.3	0.42	0.91	0.82	0.95	0.84	0.75	0.82	0.74	0.87	0.7
170407	83.2	136.52	59.6	-10.2	0.6	0.71	0.64	0.86	0.74	0.14	0.65	0.45	0.63	0.51
170602	60.9	95.55	40.2	0.2	0.4	0.82	0.84	0.95	0.79	0.88	0.85	0.72	0.81	0.66
180101	73.63	109.47	81.3	-19.7	0.81	0.85	0.34	0.79	0.66	0.39	0.42	0.29	0.57	0.51
180302	85.21	139.47	47.6	-9.6	0.48	0.82	0.77	0.93	0.82	0.65	0.78	0.63	0.76	0.66
180303	88.85	140.16	43.9	-5.3	0.44	0.81	0.81	0.94	0.82	0.71	0.82	0.67	0.78	0.67
180307	89.72	143.11	48	7.1	0.48	0.94	0.77	0.94	0.82	0.66	0.78	0.72	0.85	0.65
180308	110.1	208.9	53.1	-13.8	0.53	0.73	0.72	0.9	0.81	0.61	0.75	0.54	0.67	0.65
180504	105.93	191.75	65.7	-23.3	0.66	0.67	0.57	0.84	0.7	0.72	0.61	0.38	0.54	0.53
190009	43.23	63.81	65.2	13.3	0.65	1.18	0.57	0.9	0.75	0.58	0.71	0.66	0.73	0.58
190203	69.4	114.7	55	13.7	0.55	1	0.7	0.92	0.8	0.57	0.73	0.71	0.8	0.61
190301	77.52	124.87	54.1	-8.1	0.54	0.75	0.71	0.9	0.77	0.53	0.72	0.54	0.7	0.6
190303	43.35	64.35	53.1	-17.5	0.53	0.74	0.72	0.9	0.75	0.64	0.77	0.56	0.66	0.65
199901	49.51	72.25	68.8	23.3	0.69	1.21	0.52	0.9	0.74	0.47	0.71	0.63	0.65	0.54
199904	41.02	63.83	69.9	20.2	0.7	1.19	0.51	0.89	0.75	0.55	0.68	0.62	0.67	0.56
199907	40.44	61.76	42.8	1.7	0.43	0.94	0.82	0.95	0.83	0.79	0.82	0.76	0.89	0.72
200002	44.99	66	46.8	0.8	0.47	0.99	0.78	0.94	0.81	0.73	0.79	0.74	0.89	0.68
200101	61.52	89.88	71	-11.2	0.71	0.92	0.49	0.85	0.7	0.44	0.54	0.43	0.7	0.56
200201	65.46	97.43	74.2	-4.5	0.74	0.89	0.45	0.83	0.69	0.21	0.49	0.38	0.68	0.49
200204	46.61	79.37	58.2	-2.3	0.58	0.87	0.66	0.89	0.77	0.58	0.66	0.55	0.77	0.62
210302	44.21	66.9	47.7	-7.8	0.48	0.9	0.77	0.93	0.8	0.69	0.78	0.67	0.83	0.69
220201	78.98	131.16	59.5	-29.3	0.59	0.61	0.65	0.86	0.74	0.54	0.8	0.49	0.5	0.61
220301	58.35	91.72	48	-10.4	0.48	0.8	0.77	0.93	0.8	0.7	0.79	0.63	0.75	0.68
220303	86.31	131.35	67.7	-5.1	0.68	0.75	0.54	0.84	0.69	0.26	0.54	0.39	0.63	0.5

Station_ID	MAE	RMSE	NRMSE %	PBIAS %	RSR	rSD	NSE	d	md	cp	R2	bR2	KGE	VE
640103	67.72	94.26	125.4	60	1.25	1.38	-0.59	0.72	0.56	-0.09	0.43	0.33	0.21	0.22
80501	71.63	105.9	60.2	-25.3	0.6	0.67	0.64	0.87	0.73	0.59	0.76	0.51	0.57	0.64
90507	48.23	72.22	50.1	-10.4	0.5	0.81	0.75	0.92	0.79	0.75	0.77	0.62	0.75	0.7
90511	148.45	92.19	54.4	-3.4	0.54	0.88	0.7	0.91	0.77	0.69	0.71	0.61	0.8	0.67

Note: MAE is mean absolute error, RMSE is root-mean squared error, NRMSE is the normalized root-mean squared error, Percent Bias (pbias), RSR is the RMSE-observations standard deviation ratio, rSD is the Ratio of Standard Deviations, NSE is the Nash-Sutcliffe efficience, d is the Index of Agreement, md is the Modified Index of Agreement, cp is the Coefficient of Persistence, R2 is the coefficient of determination, bR2 is the coefficient of determination multiplied by the slope of the linear regression, Kling-Gupta efficiency (KGE), and VE is the volumetric efficiency.

ANNEX 3 - Summary Goodness of fit statistics computed when comparing station rainfall data with the TRMM gridded rainfall product.

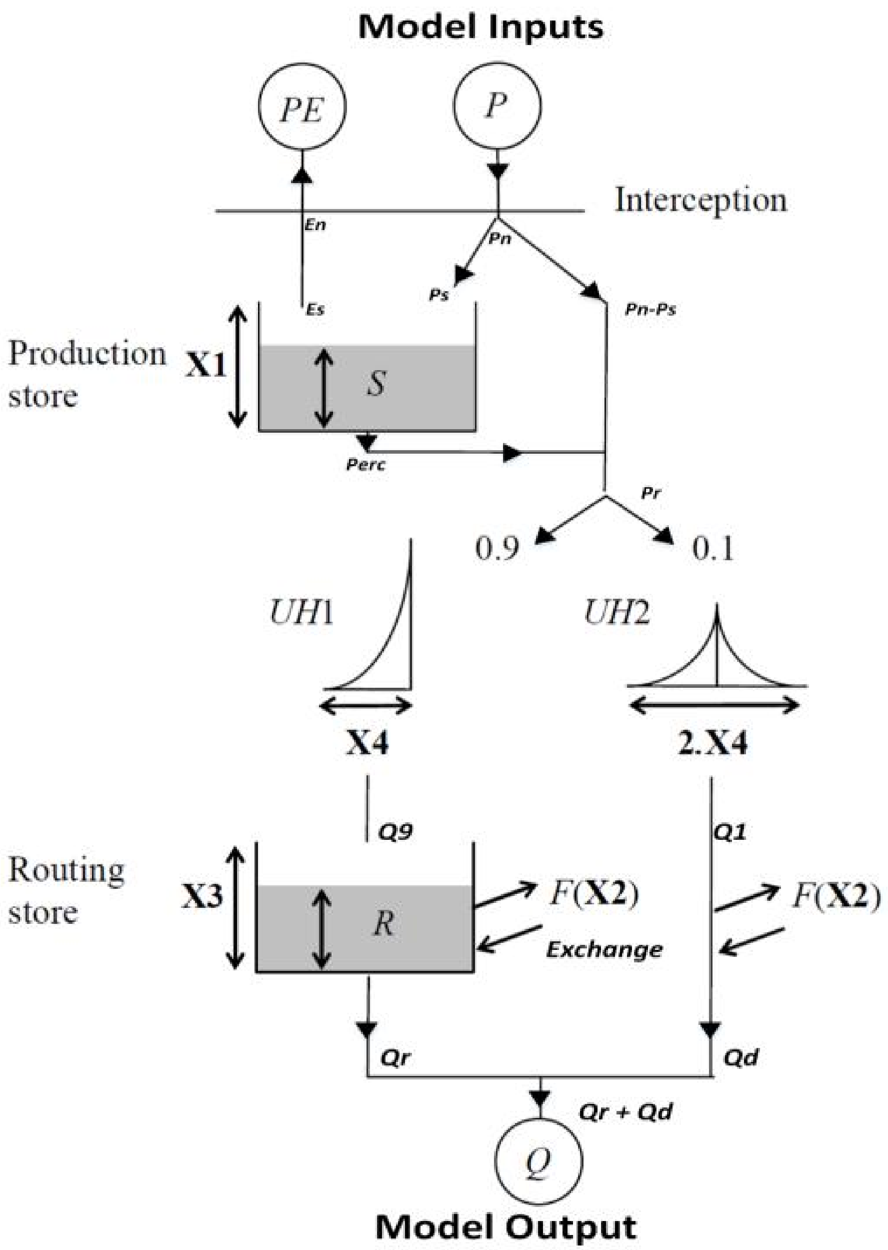
Station_ID	MAE	RMSE	NRMSE %	PBIAS %	RSR	rSD	NSE	d	md	cp	R2	bR2	KGE	VE
100401	60.5	94.29	59.5	-17.2	0.59	0.78	0.64	0.88	0.74	0.66	0.68	0.5	0.67	0.64
100509	40.78	60.34	56.7	12.4	0.57	1.07	0.68	0.92	0.78	0.7	0.74	0.71	0.8	0.67
100514	40.39	61.03	57.7	7.4	0.58	0.98	0.67	0.91	0.77	0.7	0.69	0.67	0.82	0.66
100516	41.1	56.27	56.1	22.5	0.56	1.09	0.68	0.93	0.77	0.66	0.79	0.71	0.73	0.64
100517	43.69	61.86	51.6	7.7	0.52	0.92	0.73	0.92	0.78	0.72	0.74	0.71	0.83	0.67
100605	46.45	70.14	60.9	13.6	0.61	1	0.63	0.9	0.77	0.64	0.68	0.67	0.78	0.61
100613	45.3	66.56	55.9	2.4	0.56	1.01	0.69	0.92	0.78	0.69	0.71	0.68	0.84	0.68
100617	41.35	61.81	54.7	9.9	0.55	1.01	0.7	0.92	0.79	0.66	0.74	0.74	0.83	0.68
110303	96.45	156.65	43.2	-23.9	0.43	0.65	0.8	0.93	0.81	0.71	0.94	0.65	0.58	0.68
110415	47.96	67.03	65.4	14.4	0.65	1.08	0.57	0.89	0.73	0.62	0.67	0.65	0.75	0.58
110433	72.86	101.73	100.5	49	1.01	1.3	-0.02	0.8	0.61	0.25	0.55	0.45	0.37	0.3
110434	63.47	93.25	96	54.5	0.96	1.3	0.07	0.82	0.64	0.27	0.61	0.48	0.34	0.32
110450	24.5	35.77	36.7	2	0.37	0.94	0.86	0.96	0.84	0.89	0.86	0.82	0.9	0.77
110508	47.61	69.66	73.4	9.3	0.73	0.91	0.45	0.83	0.67	0.54	0.5	0.46	0.68	0.58
110517	54	71.57	61	35.3	0.61	0.96	0.62	0.9	0.69	0.79	0.74	0.69	0.62	0.5
110518	51.07	76.76	103.3	57.2	1.03	1.27	-0.1	0.79	0.64	0.03	0.52	0.42	0.31	0.28
110523	57.05	81.88	101.9	44.5	1.02	1.45	-0.05	0.82	0.65	0.12	0.66	0.49	0.34	0.42
110524	43.17	78.15	78.8	14.8	0.79	1	0.37	0.83	0.73	0.77	0.49	0.46	0.66	0.59
110525	49.36	70.4	72.7	11.8	0.73	0.96	0.47	0.85	0.68	0.53	0.54	0.5	0.7	0.54
110605	71.06	101.59	71.2	38.1	0.71	1.07	0.48	0.87	0.71	0.62	0.67	0.6	0.57	0.47
110608	53.07	73.79	83.3	55	0.83	1.13	0.28	0.85	0.66	0.59	0.67	0.54	0.41	0.38
120202	126.8	181.28	215.4	133.7	2.15	2.02	-3.66	0.54	0.43	-2.71	0.33	0.19	-0.73	-0.47
120303	75.84	111.21	106.9	31.7	1.07	1.22	-0.15	0.74	0.58	-0.1	0.35	0.34	0.44	0.32
120313	81.81	127.47	121.5	51.6	1.21	1.45	-0.49	0.73	0.61	-0.15	0.44	0.35	0.24	0.28
120402	69.44	102.46	63.2	-19.3	0.63	0.69	0.6	0.85	0.71	0.58	0.64	0.43	0.58	0.55
120410	52.36	80.07	73.8	20	0.74	1.24	0.45	0.88	0.74	0.25	0.67	0.6	0.64	0.53
120417	48.02	72.1	58.9	8.6	0.59	1.05	0.65	0.91	0.78	0.65	0.7	0.7	0.81	0.63
120515	63.5	91.52	124.4	87.7	1.24	1.55	-0.59	0.77	0.59	0.01	0.66	0.43	-0.05	0.09
120518	46.8	71.25	59.8	13.5	0.6	1.02	0.64	0.91	0.77	0.68	0.69	0.69	0.78	0.62
120602	76.84	105.54	89.1	41.8	0.89	1.29	0.2	0.84	0.67	0.34	0.66	0.52	0.46	0.43
120712	83.1	122.33	62.8	2.6	0.63	0.74	0.6	0.86	0.71	0.45	0.61	0.49	0.66	0.59
120805	62.15	95.24	70.2	19.1	0.7	0.94	0.51	0.86	0.71	0.54	0.58	0.55	0.69	0.55
130209	43.45	60.32	69.6	35.8	0.7	1.03	0.5	0.88	0.72	0.64	0.68	0.61	0.6	0.51
130304	71.39	97.92	153.5	108.4	1.53	1.75	-1.43	0.71	0.53	-1.64	0.61	0.36	-0.34	-0.17
130307	48.11	72.87	68.4	18.8	0.68	0.99	0.53	0.87	0.72	0.64	0.61	0.59	0.71	0.52
130403	53.16	80.97	57.8	-7	0.58	0.87	0.66	0.9	0.75	0.59	0.67	0.55	0.77	0.64
130604	68.51	96.01	69.9	30.1	0.7	1.18	0.51	0.89	0.73	0.47	0.71	0.62	0.62	0.51
130705	55	84.77	37.8	5.5	0.38	0.89	0.85	0.96	0.85	0.81	0.86	0.79	0.86	0.7

Station_ID	MAE	RMSE	NRMSE %	PBIAS %	RSR	rSD	NSE	d	md	cp	R2	bR2	KGE	VE
130803	64.33	103.57	60.4	6.8	0.6	0.83	0.63	0.88	0.72	0.6	0.64	0.53	0.73	0.55
140105	47.78	70.32	77.5	23.2	0.78	1.18	0.39	0.87	0.71	0.63	0.61	0.56	0.63	0.51
140201	19.21	26.14	26	2.3	0.26	0.97	0.93	0.98	0.89	0.94	0.93	0.92	0.95	0.82
140203	43.29	64.37	80.2	52.3	0.8	1.17	0.35	0.86	0.7	0.45	0.67	0.56	0.42	0.38
140402	64.24	111.91	59.3	-7.6	0.59	0.7	0.64	0.86	0.75	0.46	0.66	0.47	0.64	0.6
140501	52.2	78.08	51	23.6	0.51	1.18	0.74	0.94	0.81	0.69	0.85	0.74	0.69	0.63
140502	59.68	92.92	63.6	28.6	0.64	1.21	0.59	0.91	0.78	0.37	0.77	0.66	0.63	0.56
140505	63.27	100.27	39.3	-10.4	0.39	0.77	0.84	0.95	0.83	0.8	0.88	0.69	0.74	0.69
140704	49.48	71.7	41.3	-6.2	0.41	0.86	0.83	0.95	0.82	0.73	0.83	0.72	0.82	0.72
150107	35.74	54.33	85	40.9	0.85	1.36	0.27	0.87	0.72	0.36	0.72	0.56	0.43	0.48
150201	42.04	59.4	63.2	7.2	0.63	1	0.59	0.89	0.73	0.56	0.64	0.6	0.79	0.58
150203	34.7	54.22	61.7	16.5	0.62	1.05	0.61	0.9	0.76	0.61	0.69	0.68	0.76	0.6
150207	32.68	48.02	51.3	13.4	0.51	1	0.73	0.93	0.8	0.77	0.77	0.76	0.82	0.64
150208	39.6	54.35	68.9	28.6	0.69	1.15	0.52	0.89	0.71	0.62	0.7	0.62	0.64	0.5
150305	42.65	65.63	53	25.4	0.53	1.09	0.7	0.93	0.81	0.43	0.81	0.72	0.71	0.66
150306	43.22	69.23	50.6	-10.5	0.51	0.81	0.74	0.92	0.79	0.71	0.75	0.6	0.75	0.67
150405	41.04	63.12	52.1	17.3	0.52	1.06	0.72	0.93	0.81	0.67	0.78	0.75	0.78	0.64
150410	33.71	49.42	30.6	-1.8	0.31	0.86	0.9	0.97	0.87	0.83	0.91	0.82	0.86	0.79
150501	38.76	66.57	42.2	13.1	0.42	1.12	0.82	0.96	0.86	0.73	0.87	0.8	0.81	0.74
150504	44.27	65.57	33	11.5	0.33	0.92	0.89	0.97	0.86	0.87	0.9	0.87	0.85	0.72
150605	57.74	81.5	38.6	-5.4	0.39	1.02	0.85	0.96	0.84	0.77	0.86	0.82	0.91	0.73
150607	67.37	106.52	44.1	-12.9	0.44	0.85	0.8	0.94	0.82	0.72	0.82	0.67	0.78	0.71
160111	30.92	50.27	45.8	-12.2	0.46	0.84	0.79	0.94	0.82	0.82	0.81	0.66	0.77	0.72
160207	78.09	132.13	76	-22.8	0.76	0.61	0.41	0.76	0.67	0.53	0.46	0.25	0.44	0.46
160208	44.7	67.16	62.5	33.2	0.62	1.12	0.6	0.91	0.76	0.7	0.75	0.67	0.62	0.52
160303	37.87	62.1	55.8	27.4	0.56	1.08	0.68	0.93	0.8	0.61	0.78	0.71	0.69	0.6
160401	27.83	42.76	30.5	8.8	0.31	1.01	0.91	0.98	0.88	0.89	0.92	0.9	0.9	0.77
160402	70.67	104.23	86.8	66	0.87	1.41	0.24	0.87	0.71	0.1	0.8	0.56	0.22	0.29
160406	54.91	90.19	65.6	38.5	0.66	1.11	0.56	0.9	0.77	0.56	0.72	0.65	0.57	0.49
160407	47.1	72.85	46.3	-11	0.46	0.92	0.78	0.94	0.83	0.74	0.8	0.68	0.83	0.7
160501	54.25	84.5	53.2	12.3	0.53	1.06	0.71	0.93	0.81	0.64	0.76	0.75	0.81	0.61
160506	72.23	111.03	74.4	39.5	0.74	1.05	0.44	0.86	0.7	0.14	0.62	0.59	0.55	0.4
160602	90.06	140.02	103.7	59.1	1.04	1.43	-0.09	0.81	0.66	-0.14	0.6	0.46	0.24	0.23
160605	58.66	81.77	51.1	25.2	0.51	0.98	0.74	0.93	0.78	0.66	0.79	0.77	0.72	0.56
160704	80.33	151.37	47.6	-5.2	0.48	0.8	0.77	0.93	0.81	0.77	0.78	0.62	0.77	0.67
170104	38.23	60.28	70.9	26.7	0.71	1.27	0.49	0.9	0.76	0.57	0.73	0.62	0.6	0.55
170105	37.5	52.52	47.1	13.5	0.47	1.02	0.78	0.94	0.79	0.81	0.81	0.79	0.83	0.65
170107	29.47	43.8	39.9	4	0.4	1.02	0.84	0.96	0.83	0.87	0.85	0.84	0.91	0.72
170205	46.61	73.94	54.9	23	0.55	1.05	0.69	0.93	0.8	0.68	0.76	0.73	0.73	0.59
170206	39.4	59.62	41.3	20.5	0.41	1.14	0.83	0.96	0.85	0.79	0.9	0.79	0.74	0.72
170302	67.55	112.32	80	23.4	0.8	1.11	0.35	0.85	0.74	0.4	0.54	0.53	0.63	0.46
170304	65.86	96.87	65.2	39.1	0.65	1.2	0.57	0.91	0.77	0.62	0.79	0.65	0.55	0.5
170306	60.79	92.69	54.6	20.3	0.55	1.13	0.7	0.93	0.81	0.64	0.79	0.72	0.73	0.63
170403	31.87	52.52	23.2	-2.4	0.23	0.89	0.95	0.98	0.91	0.91	0.95	0.87	0.89	0.83

Station_ID	MAE	RMSE	NRMSE %	PBIAS %	RSR	rSD	NSE	d	md	cp	R2	bR2	KGE	VE
170406	52.99	85.84	32.8	-3.6	0.33	0.9	0.89	0.97	0.88	0.85	0.89	0.81	0.88	0.77
170407	160.48	239.18	211.6	175	2.12	2.58	-3.89	0.67	0.5	-11.9	0.93	0.36	-1.36	-0.75
170602	53.72	104.09	44.2	-3.9	0.44	0.87	0.8	0.94	0.82	0.85	0.8	0.68	0.83	0.7
180101	74.12	106.8	77	-20.4	0.77	0.83	0.4	0.81	0.67	0.38	0.48	0.33	0.59	0.53
180302	41.4	70.09	21.6	2.6	0.22	0.99	0.95	0.99	0.93	0.92	0.95	0.94	0.96	0.86
180303	48.45	78.88	24.6	8.1	0.25	1.01	0.94	0.98	0.91	0.91	0.95	0.92	0.91	0.82
180307	78.16	128.59	39.7	12.5	0.4	0.98	0.84	0.96	0.86	0.79	0.86	0.85	0.85	0.71
180308	86.3	165.28	41.4	-6	0.41	0.82	0.83	0.95	0.86	0.79	0.84	0.69	0.8	0.73
180504	80.79	130.6	47.8	-16.8	0.48	0.73	0.77	0.92	0.76	0.84	0.82	0.59	0.67	0.63
190009	42.24	59.54	60	17.7	0.6	1.18	0.64	0.92	0.77	0.66	0.76	0.69	0.72	0.61
190203	62.46	104.24	46.9	3.2	0.47	0.87	0.78	0.93	0.82	0.66	0.78	0.69	0.83	0.68
190301	60.43	96.52	39.9	0.5	0.4	0.84	0.84	0.95	0.84	0.75	0.85	0.74	0.82	0.71
190303	30.93	48.97	40.5	9.3	0.41	1.03	0.83	0.96	0.84	0.8	0.86	0.83	0.88	0.75
199901	31.91	49.47	43.6	1.9	0.44	0.99	0.81	0.95	0.83	0.84	0.82	0.79	0.9	0.74
199904	31.86	46.3	43.7	17.1	0.44	1.04	0.81	0.95	0.82	0.85	0.85	0.8	0.81	0.69
199907	33.34	52.99	35.1	-10.6	0.35	0.81	0.88	0.96	0.86	0.87	0.91	0.76	0.77	0.8
200002	35.06	52.18	38	4.4	0.38	0.95	0.85	0.96	0.84	0.83	0.86	0.83	0.9	0.74
200101	47.89	77.21	58.3	-6	0.58	0.87	0.66	0.9	0.77	0.66	0.66	0.55	0.77	0.65
200201	47.61	71.44	56.7	19.8	0.57	0.96	0.68	0.91	0.76	0.56	0.72	0.7	0.75	0.57
200204	30.8	54.84	42.4	8.7	0.42	0.98	0.82	0.95	0.85	0.81	0.83	0.82	0.87	0.75
210302	39.2	60.27	42.4	-6	0.42	0.87	0.82	0.95	0.82	0.75	0.82	0.71	0.83	0.73
220201	62.93	107.93	46.9	-10.1	0.47	0.71	0.78	0.92	0.81	0.73	0.82	0.63	0.68	0.7
220301	60.19	93.13	47.6	-5.2	0.48	0.78	0.77	0.92	0.79	0.7	0.79	0.64	0.75	0.68
220303	97.12	152.45	85.3	37.6	0.85	0.84	0.27	0.78	0.63	-0.35	0.39	0.32	0.45	0.25
640103	62.12	92.21	122.7	52.2	1.23	1.48	-0.52	0.75	0.61	-0.06	0.47	0.36	0.23	0.29
80501	55.35	82.49	46.9	-15.7	0.47	0.83	0.78	0.93	0.8	0.75	0.82	0.66	0.75	0.73
90501	43.32	64.23	44.6	1.3	0.45	0.92	0.8	0.94	0.82	0.8	0.8	0.74	0.87	0.73
90511	51.55	73.21	43.5	-4	0.44	0.93	0.81	0.95	0.81	0.79	0.81	0.74	0.87	0.74

ANNEX 4 – GR4J Model Description

GR4J is a lumped conceptual rainfall-runoff model that converts daily areal rainfall (P) and potential evapo-transpiration (PE) into simulated daily streamflow. For a watershed, runoff is simulated by first determining net rainfall (Pn) by comparing P and PE. This assumes an interception storage of zero. When P is less than the PE, an actual evapotranspiration rate is determined using the level water stored in the soil surface or production store to calculate the quantity of water that will evaporate from the store. When P is greater than PE, a net precipitation (Pn) is calculated as the difference between P and PE. The Pn is then divided into two components - part is stored in the soil surface (production store, S) and the rest is routed through the channel. Flow percolated (Perc) from the production store is combined with routing flow to get the total routed flow (Pr). Pr is routed in two parts : 10% of Pr is routed using a single unit hydrograph, while the remaining 90% is routed via a unit hydrograph and a non linear routing store (R). Ground water exchange is determined by applying water gain or loss function (F) is applied to both flow components. The total stream flow is then computed as the sum of outflows from both unit hydrographs Qr and Qd (Coron et al., 2017; Perrin, Michel, & Andréassian, 2003).



GR4J model structure and flow chart. P is rainfall, PE is potential evapotranspiration, En is net evapo-transpiration, Es is actural evapo-transpiration, Pn is net rainfall, Perc is percolation, Pr is total amount of water reaching routing function, Ps is amount of net rainfall that goes to the production store, Qd is direct flow, Qr is routed flow, UH1 and UH2 are unit hydrographs 1 and 2.

In the GR4J model, four parameters have to be optimized during model calibration: x1 : maximum capacity of the production store (mm) also known as Soil moisture accounting (SMA), x2 : water exchange coefficient (mm), x3 : the routing store (mm) and the x4 : Unit Hydrograph time base/ lag time (days). The calibration procedure involves two distinct steps. First a systematic inspection of the parameters space is performed to determine the most likely zone of model convergence using either a direct grid-screening method or constrained sampling based on empirical parameter databases. A steepest descent local search procedure is then used to find the optimum parameter set (Coron et al., 2017).

GR4J model calibration parameter ranges at the 80% confidence interval.

Parameter	Median Value	80% Confidence Interval
x1 (mm)	350	100 - 1200
x2 (mm)	0	-5 - 3
x3 (mm)	90	20 - 300
x4 (days)	1.7	1.1 - 2.9