



Mekong River Commission
For Sustainable Development



Mekong Low Flow and Drought Conditions in 2019–2021

Hydrological Conditions in the Lower
Mekong River Basin

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Technical Report

Mekong River Commission Secretariat

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Mekong River Commission

Documentation and Learning Centre

184 Fa Ngoum Road, Unit 18, Ban Sithane Neua, Sikhottabong District, Vientiane 01000, Lao PDR

Telephone: +856-21 263 263 | E-mail: mrcc@mrcmekong.org | www.mrcmekong.org

Contents

Acronyms and abbreviations	vi
Executive Summary	vii
1 Introduction	1
1.1 Background	1
1.2 Objectives.....	3
2 Flows and the Functioning of the Mekong River System	5
2.1 Natural hydrological characteristics of the mainstream.....	5
2.2 Changing hydrological characteristics	5
3 Drought management in the 1995 Mekong Agreement	8
3.1 Notification, prior consultation and agreement (PNPCA).....	8
3.2 Maintaining flows on the mainstream (PMFM).....	9
3.3 A shifting emphasis.....	11
4 Methodology and Data	12
4.1 Scope of study	12
4.2 Hydrological datasets and stations.....	12
4.3 Precipitation data and drought Indexes	15
4.4 Storage data	15
5 Analysis of the Results	17
5.1 Mainstream hydrology	17
5.2 Reverse flows into the Tonle Sap Lake	23
5.3 Changes in storage	26
5.4 Changes in rainfall patterns.....	29
5.5 Climate change and <i>El Nino/La Nina</i>	31
6 Discussion	33
6.1 Previous studies.....	33
6.2 This report’s heuristic analysis	34
6.3 Reasonable and equitable use.....	36

7	Drought Management Options	38
7.1	Building more storage	38
7.2	Managing water allocations	39
7.3	Other adaptation strategies	40
8	Conclusions	41
9	Recommendations	42
10	References	43
	Annex A: Do low flows influence the fish catch in the Tonle Sap River and Lake?	48
	Annex B: Accumulative rainfall for 2018-2021.....	54
	Annex C: Monthly rainfall anomalies for 2018-2021.....	60
	Annex D: Standardised Precipitation Index and Combined Drought Index for 2018-2021	65
	Annex E: Characteristics of water level of the Mekong mainstream for 2018-2021	74
	Annex F: Quarterly global temperature anomaly for 2018-2021.....	77

List of figures

Figure 1.	Map of the Lancang-Mekong Basin. The Lancang-Mekong Basin is the Mekong Basin in MRC documents, composed of two parts: the Upper Mekong Basin (Lancang Basin in China) and Lower Mekong Basin.....	2
Figure 2.	The monomodal flood peak characteristics of the Mekong mainstream	5
Figure 3.	Expected changes in the mainstream flows with developments in the Basin.	6
Figure 4.	The different approaches to notification, prior consultation and special agreement outlined in Article 5 of the 1995 Mekong Agreement.	9
Figure 5.	Criteria on water flow with the seasons defined in the PMFM.....	10
Figure 6.	Location of key hydrological stations for flow monitoring on the Mekong mainstream. .	14
Figure 7.	Characteristics of discharge of the Mekong mainstream at (1) Jinghong, (2) Chiang Saen, (4) Nong Khai, compared to conditions of 2008-2017.....	18
Figure 8.	Characteristics of discharge of the Mekong mainstream at (5) Nakhon Phanom, (6) Mukdahan, (7) Pakse and (8) Stung Treng, compared to conditions of 2008-2017.....	19
Figure 9.	Accumulated flows at mainstream stations for the dry seasons of 2018-2021.	21
Figure 10.	Accumulated flows at mainstream stations for the wet seasons of 2018-2021.	22
Figure 11.	Characteristics of water level of the Tonle Sap Lake and Delta at (9) Phnom Penh Port, (11) Kampong Loung, (12) Tan Chau and (13) Chau Doc, compared to conditions of 2008-2017.....	24
Figure 12.	Characteristics of accumulated reverse flows to the Tonle Sap Lake for 2018-2021, compared to the minimum, maximum and average of 2008-2017.	25
Figure 13.	The Configuration of the Lancang Cascade Hydropower Projects.	26
Figure 14.	Storage behaviours for Xiaowan and Nuozhadu Reservoirs over the annual cycle for 2018 to 2021, suggested from satellite data.	27
Figure 15.	Storage behaviours for Lao PDR reservoirs over the annual cycle for 2018 to 2021, suggested from satellite data.	28
Figure 16.	Pattern of monthly rainfall and its anomaly for 2018-2021.....	30
Figure 17.	Rainfall anomaly maps for the Mekong Basin for August 2018, 2019, 2020, 2021.	30

Figure 18. A conceptual diagram of the impacts of building storage to capture surplus water. 38

Figure 19. A conceptual diagram of the yield to storage curve. 38

Figure 20. The days of MAR that can be stored in major basins in the world..... 39

List of tables

Table 1.	Data availability for the Mekong mainstream and Tonle Sap Lake stations.....	13
Table 2.	The categories of large dams used on the Mekong Dam Monitor site, the total number of dams in each category, and the total active storage available.	15
Table 3.	Estimated total active storage in each riparian country.	16
Table 4.	The difference in accumulated flows at mainstream stations for the wet and dry seasons of 2018-2021, versus the average accumulated flows of 2008-2017.	20
Table 5.	The percentage difference between accumulated flows and average of 2008-2017.....	20
Table 6.	Summary of accumulated reverse flows to the Tonle Sap Lake for 2008-2017.....	25

Acronyms and abbreviations

LMB	Lower Mekong Basin
MAR	Mean Annual Runoff
MRC	Mekong River Commission
PMFM	(MRC) Procedures for Maintenance of Flows on the Mainstream
PNPCA	(MRC) Procedures for Notification, Prior Consultation and Agreement
UMB	Upper Mekong Basin

Executive Summary

Background

The Mekong River Basin is separated into the Upper Mekong River Basin (UMB)¹ in China and Myanmar, and the Lower Mekong River Basin (LMB) that falls within the territories of the MRC Member Countries: Cambodia, Lao PDR, Thailand and Viet Nam. The UMB makes up about 20% of the total Basin area and contributes 64 km³ or 13.5% of the Mean Annual Runoff (MAR) of 475 km³. The hydrology of the Mekong mainstream is dominated by the timing and intensity of the southeast Asian monsoon. This has produced a single monomodal flood peak period during the wet season. These seasonally variable flows and the timing of the first flood pulse have maintained the natural ecosystem functioning, sustained livelihoods, and maintained the region's food security in the Mekong Basin for centuries.

However, over the last three years, flows on the Mekong mainstream have decreased to levels not seen in more than 60 years. This has resulted in knock-on impacts on fisheries and agriculture and the people's livelihoods of the Mekong Delta. These conditions have persisted through to the wet seasons of 2020 and 2021. The ramifications of these extreme low flows are wide-ranging and have been extensively reported in the press. Scientific reports and publications, and press articles have variously apportioned responsibility on the unprecedented drought, climate change, an *El Nino* event, and the impacts of storage operation in large reservoirs in the UMB. However, as the Mekong Basin lies in a geopolitically complex region of the world, different perspectives may have played a role in shaping these reporting and studies' outcomes. This report unravels the underlying drivers of the extremely low flows and drought based on an analysis of the available data. It then suggests potential measures to address and mitigate the impacts of the hydrological droughts and storage on the Basin's people.

Hydrological drivers

In general, increased storage in the Basin increases dry season flows, decreases wet season flows and delays the first flood pulses compared to the historical natural flow regime. But variable rainfall and delays in the monsoon rains also alter flow regimes. Changing flow regimes affect ecosystem functioning. The Tonle Sap Lake acts as a bellwether for the combination of these factors. The water level difference between the Tonle Sap Lake and the Mekong mainstream drives the annual reverse flow from the Mekong River into the Lake. This typically contributes some 50% to the total inflows to the Lake. Fish abundance and diversity in the Tonle Sap Lake/River has been positively linked to higher lake levels. Many livelihoods depend on this fish production. The gradual emptying of the Lake into the following dry season helps reduce seawater intrusion and provides a vital source of freshwater for communities in the Mekong Delta.

The recent delayed and reduced reverse flows to the Tonle Sap Lake appear to have affected fish catches and resulted in considerable hardship for the Delta people, as has been extensively reported in the press. Understanding and managing these dynamics will be increasingly important as climate change and additional storage built in the Basin exacerbate these impacts, positively and negatively.

¹ Known as the Lancang in China.

Results of previous studies

There have been three main studies/analyses of the 2019 low flow conditions.

1. ***Eyes on Earth (EoE)*** study (April 2020²) and data are based on remote sensing to determine reservoir water levels, as well as the Surface Wetness Index and rainfall data to determine flows, which were calibrated against the MRC's flow gauge at Chiang Saen. This is used to model the 'natural' flow, which is compared to the actual flows at Chiang Saen, with the assumption that any deficit in flows was due to the storage in the UMB.
2. ***Tsinghua University*** in collaboration with ***China Institute of Water Resources and Hydropower Research*** (July 2020³) used slightly different approaches and input rainfall data. The Standardised Precipitation Evapotranspiration Index and the Standardised Precipitation Index were used to assess the intensity and extent of drought over the whole Mekong River Basin. River flows were based on the THREW hydrological model, and rainfall input data came from both surface and satellite rainfall measurements across the whole Basin. The impacts of the storage in the UMB were also based on determining 'natural' pre-storage flows and comparing them to post storage flows. This study emphasises drought as the main driver. This is based on the observation that, while the Lancang River contributes significantly to the annual discharge at Chiang Saen (64.4%), the proportion drops to 39.5% at Nong Khai and 14.3% at Stung Treng. Thus, it argues that reduced flows from the UMB cannot be the primary driver of the drastically lower flows noted further downstream.
3. ***The MRC Secretariat analysis*** (April 2020⁴, August 2020⁵, May 2021⁶, June 2021⁷) is based on a heuristic approach⁸ using observed rainfall, flows and drought indexes.

The MRCS highlights the unusual intensity of the drought. The previous assessments used slightly different approaches and datasets and came up with subtly different results on the impacts of storage and drought on flow. They, however, drew different conclusions on the relative contributions of the drivers of the hydrological drought.

Data and methodology

The scope of the current study covers the temporal scale of January 2018–December 2021 (focusing on the 2019, 2020 and 2021 wet and dry seasons) and spatial scale of available data from meteorological and hydrological observation on the whole Mekong River Basin.

² See [SIP \(2021\)](#) for a full report.

³ See [Tsinghua University \(2021\)](#) for a full report.

⁴ See [MRC \(2020a\)](#) for a full report.

⁵ See [MRC \(2020b\)](#) for a full report.

⁶ See [MRC \(2020c\)](#) for a full report.

⁷ See [MRC \(2021a\)](#) for a full report.

⁸ A heuristic, or heuristic technique, is any approach to problem-solving that uses a practical method or various shortcuts in order to produce solutions that may not be optimal but are sufficient given a limited timeframe or deadline (Chen, 2021).

Observations

Flows in the Mekong mainstream from 2019 to 2021

The flows along the length of the mainstream from 2019 to 2021 (*'the drought years'*) show:

- Wet season flows into the LMB (at Chiang Saen) in the drought years were below the average of 2008–2017. Dry season inflows were above the average of 2008–2017, with the exception of the 2020 dry season. This trend persisted along the whole Mekong mainstream.
- In the wet season, the total flow deficit (the difference between the long-term volume and current volume) in the wet season increases downstream.
- There are short duration wet season flow peaks in all three drought years at sites further downstream – reducing from five months of June-October to four months of July-October.
- While 2019 had higher-than-normal dry season flows, the trend was for lower-than-normal dry season flows in 2020 and to some extent in 2021.

Flows in the Mekong mainstream are determined by:

- The total amount of available storage in the Basin over the year.
- The ratio of the upstream catchment size.
- The total volume of storage at the start of the wet season.
- The timing and volume of the southeast Asian Monsoon.

Impacts on the reverse flows into the Tonle Sap Lake

Observations of water levels at Phnom Penh and in the Tonle Sap Lake show:

- The reverse flows in the drought years were delayed and reduced in volume.
- The pattern of the Lake water levels in 2019, 2020 and 2021 are the lowest on record.
- The reduced Lake volumes are likely to be the primary driver behind the low fish catches and problems reported by people in Mekong Delta.
- The 2019 total reverse flow volume is close to the average for 2008-2021.
- The total reverse flows in 2020 and 2021 are 58% and 51% of the average total reverse flow volume of 2008-2021 and are the lowest and second lowest since 2008.

The reverse flow timing and volume is determined by:

- The water levels differences between the Lake and Mekong Mainstream.
- The duration of this disparity.
- Rainfall and runoff from the Tonle Sap Lake/River local catchment.
- Dredging and other factors affecting the river channel morphology.

Changes in storage patterns

While it is difficult to draw firm conclusions without all inflow and outflow data and water balance calculations for all the main storage reservoirs, the following deductions are possible with the data at hand:

- The total water 'held back' on the UMB's two largest reservoirs in 2019 was less than that in 2018, 2020 and 2021. This was most likely due to much lower-than-normal rains at the start of the wet season.
- This did not amount to storing *all* the inflow in the wet season of 2019, as releases were required to generate power.

- The impacts of the lower storage at the end of 2019 carried over into the 2020 dry season (operators would likely have been cautious over releasing additional water while facing a possible repeat of the 2019 wet season).
- Dry season contributions from storage in 2020 would have been lower than in 2019 as a result. This is reflected in the atypical lower-than-normal dry season flows in 2020.
- By the end of 2020, total storage in the Basin was closer to normal levels, and in 2021 the dry season contributions to flow in the mainstream were more typical.
- Compensation releases to correct the *timing of the reverse flows* would have to start in June, when storage is at its lowest levels. This would pose a considerable risk to power production.
- Compensation releases to correct the *volume of the reverse flows* would be more viable in August when storage is closer to full supply levels and in years where the UMB experiences good rainfall.

The factors affecting changes in storage are:

- The disparity between inflows and outflows (including evaporative losses).
- Inflows are affected by the rainfall runoff over the upstream catchment, as well as the operations of any upstream reservoirs.
- The outflows are affected by power demands and the requirements of any Power Purchase Agreements, as well as spillages or deliberate releases to the downstream river.
- Operators who hold back storage to minimise the risks to generation in the upcoming months.

Rainfall anomalies

The following deductions can be made from the rainfall and drought indexes data:

- Rainfall in 2018 was higher than average for January through to August. Total rainfall over the LMB dipped below average only in the latter part of the wet season, from September to December.
- In the 2019 wet season, precipitation in the UMB was considerably below normal to normal, hence the reduced storage noted in that year.
- In June and July, 2019 rainfall was below normal in the LMB. However, the higher-than-normal rain in August 2019 explains the short flow peaks at Nong Khai and the downstream stations in September 2019.
- The year 2020 is the driest year for the reporting period. In 2020 every month, except in October, rainfall was below normal. The rainfall anomaly maps for 2020 show that this was widespread across the LMB.
- In 2021 the rainfall patterns over the LMB showed the impacts of the delayed monsoons. Climate change and the *El Nino* event are likely to have contributed to the delayed and reduced monsoon rain.

The factors affecting changes in rainfall are:

- Climate Change.
- The timing of the onset and end of the monsoon rains.
- The *El Nino - La Nina* phenomenon.

Conclusions

This report draws the following general conclusions:

- The total storage in the UMB in 2019 was lower than usual due to the lower-than-normal precipitation over the UMB in the wet season. This carried over into the dry season of 2020,

when less water was released. This accounts for the lower-than-normal flow contributions from the UMB in the 2019 wet season, and the 2020 dry season.

- Apart from 2019, the patterns and volumes of water stored in the UMB have been similar since 2015⁹. However, the extremely low flows in the LMB due to the lower-than-normal rainfall over the UMB have only been evident in the LMB in the drought years of 2019-2021.
- At Chiang Saen, the total difference in the volume of flows in the wet seasons of 2019, 2020 and 2021 – compared to the average have been -28.50 km^3 , -21.38 km^3 , and -19.73 km^3 , respectively. At Stung Treng, these differences have been -90.80 km^3 , -99.63 km^3 , and -68.46 km^3 , respectively.
- Rainfall over the LMB in the first half of the wet season (June to August) has been lower since 2019, with particularly low rainfall in 2020. However, the latter part of the wet season (September and October) saw higher than normal and patchy rainfall, reflecting the delayed monsoons.
- This has resulted in a later start and longer duration of the reverse flows into the Tonle Sap Lake, with the overall reverse flow volumes and Lake levels for 2020 and 2021 being the lowest on record.

The flow patterns in the LMB are driven by a variety of factors, underpinned by the rainfall-runoff characteristics, and how much of that runoff is stored in the wet season and released in the dry season. The storages have a range of positive and adverse effects on economic activities, livelihoods and ecological functioning, beyond just the changes in flow regimes. But for the purposes of this report, the following conclusions can be drawn from the following two tables. The first presents the differences in the wet and dry season accumulated flows, versus the average accumulated flows of 2008-2017. The second expresses this as a percentage.

The difference between accumulative flows and average flows in the LMB

Volume (km ³)	2018		2019		2020		2021	
	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
Chiang Saen	7.85	6.91	13.57	-28.50	-5.62	-21.38	0.85	-19.73
Nong Khai	6.43	21.52	9.35	-64.05	-11.82	-47.11	-4.10	-41.62
Nakhon Phanom	10.99	48.00	17.66	-105.95	-14.57	-84.52	-1.40	-78.06
Mukdahan	12.54	58.01	18.80	-97.82	-10.96	-87.71	0.38	-80.00
Pakse	7.38	45.63	13.53	-94.18	-17.29	-91.82	-3.07	-75.54
Stung Treng	12.36	64.29	15.03	-90.80	-15.36	-99.63	2.55	-68.46

⁹ The two largest reservoirs on the UMB were commissioned in 2010 (Xiaowan) and 2014 (Nuozhadu).

The percentage difference between accumulative flows and average flows in the LMB

Percentage (%)	2018		2019		2020		2021	
	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
Chiang Saen	131	113	154	46	77	60	103	63
Nong Khai	120	121	129	39	64	55	87	60
Nakhon Phanom	123	123	137	48	69	59	97	62
Mukdahan	123	127	135	55	80	60	101	63
Pakse	113	117	124	64	70	65	95	71
Stung Treng	119	120	123	71	76	69	104	78

Note: Figures over 100% indicate higher-than-normal flows, those below 100% indicate lower-than-normal flows.

- A general pattern of higher dry season flows and lower wet season flows remains true to the heuristic approach that water is stored in the wet season and released in the dry season.
- Wet season flows into the LMB at Chiang Saen were consistently lower over 'the drought years' of 2019-2021. This is particularly true for the 2019 wet season, which saw accumulated flows of only 46% of the average.
- The severe drought over the UMB over the 2019 wet season meant that less water was stored, and this reduced power production releases and the two largest reservoirs did not reach full supply levels. This reduced dry season inflows to the LMB in 2020.
- The total cumulative rainfall over the LMB has been considerably lower over the drought years, and rains have been delayed by several months.
- This has delayed the start of the reverse flows into the Tonle Sap Lake, decreased the total volume of the reverse flow, and extended the period of the reverse flows.
- This appears to have decreased the abundance and biomass of fish in the Tonle Sap Lake/River and created hardship for the people's livelihoods in the following dry season. The scale and severity of the impact needs further data collection and study.

Moreover, ...

- While the two largest reservoirs in the UMB were commissioned in 2010 (Xiaowan) and 2014 (Nuozhadu), flows in the LMB reached extremely low levels only from 2019 to 2021. This points to the lower rainfall as being the main driver of the low flows in these years.
- Further weight to this comes from the observation that the 'deficit' in flows increases downstream, and the reduced flows at Chiang Saen are 31% of those at Stung Treng.
- The pattern of rainfall of the LMB in the drought years may be associated with the *El Nino* event as well as climate change, which highlights the need for operational management models/tools going forward.
- The opportunities for active management of the flows using current storage are limited. But it *may be possible* to adjust the flows using all the existing storage.
- Any model to support these operations must balance the risks to hydropower generation with the benefits in terms of the timing and volume of the reverse flows into the Tonle Sap Lake.
- As the wet season progresses, greater certainty will emerge over the risks to energy production (there will be greater certainty over the wet season rainfall and hence the likely levels of storage at the end of the wet season).

- Other drought management options like water allocation planning in case of drought year should also be explored.

Flow and drought management in the 1995 Mekong Agreement

The underlying principle behind Article 5 (Reasonable and Equitable Use), Article 6 (Maintenance of Flows on the Mainstream) and Article 26 (Rules for Water Utilisation and Inter-basin Diversion) of the 1995 Mekong Agreement is that during the wet season, there is enough water to satisfy the needs of all the MRC Member Countries. But during the dry season, upstream abstractions (or diversions) of the water could compromise downstream use. The MRC Member Countries, emphasising the territorial integrity principle, also wanted to minimise the need for interventions by the MRC in the management of their portion of the Basin. The upshot of this was that different ‘rules’ would apply to the wet and dry seasons.

Drought management is underpinned by Articles 5 and 6 of the Agreement, while Article 26 provides for the development of ‘*Rules for Water Utilisation and Inter-Basin Diversions*’, which would give effect to these Articles. The maintenance of flows on the mainstream under Article 6 was intended to be a dynamic process of sharing *surplus water* determined by flow forecasts. Under the current conditions this means determining the available active storage over and above the demands during the upcoming dry season. Article 5 provides for increasing levels of engagement determined by hydrological (tributary and mainstream), temporal (wet and dry seasons) and geographical (intra and inter-basin diversions) factors. Drought management operations would be outlined in notifications or captured as conditions as part of the prior consultation or agreement processes. However, the current implementation of the Procedures for Notification, Prior Consultation and Agreement (PNPCA) and Procedures for Maintenance of Flows on the Mainstream (PMFM) focuses more on a monitoring and reporting process rather than active management. This appears to reflect a level of engagement, which the Member Countries are currently more comfortable with.

However, the Siem Reap Declaration of 2018, the Basin Development Strategy for 2021–2030, and the MRC Strategic Plan for 2021–2025 all recognise the need for a more active operational management approach to droughts and floods.

Having the right understanding

Conclusions can only be drawn with an understanding of the hydrological conditions across the entire Mekong Basin for the relevant period. The two large storage reservoirs in the UMB (Xiaowan and Nuozhadu) hold back wet season flows, that is what they were built for. In 2019, the net storage over the wet season was lower-than-normal, most likely due to the reduced inflows because of the drought conditions. The storage on the UMB clearly has an impact on Mekong mainstream flows in the LMB. However, it is evident from the analyses done for this report, that the lower rainfall over the LMB was the main driver of the low flows in the Mekong mainstream downstream of Nong Khai, and the reduced and delayed reverse flows into the Tonle Sap Lake over the last three years (2019–2021).

However, a more pertinent and important issue, in the line with the principle of reasonable and equitable development codified in both the 1955 Mekong Agreement or the 1997 UN Convention on the Non-navigational use of Shared Watercourses, is whether and how the riparian countries, including upstream countries, can proactively act and cooperate over the last three years, particularly in light of the severe droughts in the LMB.

Recommendations

The following recommendations are made:

1. A more conclusive answer to the question of the proportion of the flow that is held back in the storage reservoirs versus the reduced inflows due to ‘drought’ or increased inflows due to ‘flood’ is most reliably based on water balance modelling in each reservoir, which requires data that is not yet available to the MRC or previous studies.
2. A ‘operational model’ of the whole Mekong River Basin needs to be built. This model should include the management and storage operations:
 - a. be updated in near real-time using the information on the active storage across the whole Basin.
 - b. present and analyse options to determine the impacts of releases on the timing and volume of the reverse flow for the remainder of the wet season and forecasts of the seasonal rainfall/runoff across the Basin.
 - c. outline the risks to energy production based on the options tested in point (b).
 - d. be based on the water releasing infrastructure at each large reservoir that is included in the model, i.e., could it be physically possible to make compensation releases?
3. Options to build more storage, operated primarily for water security enhancement, should be explored per the direction of the Basin Development Strategy 2021-2030. This should address:
 - a. the identification of suitable sites and the volumes of water that could be stored.
 - b. the potential adverse effects on resettlement, sediment transport and aquatic ecosystems.
 - c. the institutional arrangements required for a project coordination authority.
4. Given the consequences of extremely low flows and as per the proposal at the 25th MRC Dialogue Partner Meeting with China and Myanmar in 2021 on future cooperation, an enhanced or joint notification mechanism should be established as soon as possible. This should inform all the Mekong countries of emerging flood and drought conditions, to facilitate emergency response.
5. The Basin Development Strategy 2021–2030 clearly draws out the importance of enhanced information sharing and coordinated operation management of reservoirs and hydropower dams, particularly for transboundary flow management, and emergency situations. Toward this end, there is a strong need for more proactive cooperation approaches, bolder leadership and collective action from all the MRC Member Countries as well as China across the entire Lancang-Mekong River Basin.

The above recommendations will be further explored, discussed and worked with the MRC Member Countries, China and the LMC Water Center, in ongoing work such as the Joint Study on the Changing Hydrological Conditions and Adaptation Strategies as well as the Proactive Regional Planning.

1 Introduction

1.1 Background

The Lancang-Mekong River (Figure 1) originates in the Qinghai Province of China, where it is called the Lancang River. The river flows southward into Yunnan Province before leaving China near Chiang Saen in northern Thailand. It then forms the border between Lao PDR and Thailand. Further downstream, the Mekong mainstream falls entirely within Lao PDR before again forming a common border with Thailand at Chiang Khan. Yet further downstream, the mainstream again falls within the territory of the Lao PDR just upstream of Pakse. The Mekong then flows into Cambodia just downstream of the Khong fall area and the Don Sahong Hydropower Project. The Mekong River finally empties into the sea in Viet Nam through the Mekong Delta.

The Upper Mekong Basin¹⁰ makes up 164,400 km² or about 20% of the whole Mekong Basin. It contributes some 64 km³ or about 13.5% of the total Mean Annual Runoff (MAR) of the Mekong of 475 km³ (MRC, 2019a; MRC/MWR, 2016). The Lower Mekong Basin covers a total drainage area of some 600,000 km² (Li et al., 2017). The timing and intensity of the southeast Asian Monsoon dominate the streamflow in the river, contributing to a single monomodal flood peak period during the wet season¹¹ (June to November). These seasonally variable flows and the timing of the first flood pulse have contributed to sustaining livelihoods, maintaining food security, and supporting ecosystem functioning for centuries (Hecht et al., 2019). Alterations to these natural flow characteristics of the river could adversely affect the ecosystem functioning and the population that depends on the Mekong's ecological services for their livelihoods.

However, recently, the proliferation of hydropower dams throughout the Mekong Basin and unusually severe droughts are disrupting flow patterns. Drought is considered one of the most complex natural disasters, changing flow patterns in the river, reducing the water available for irrigation purposes and reducing the yields of rainfed crops. This impacts the well-being of communities dependent on agriculture and has ripple effects throughout the economy (Keovilignavong et al., 2021). In addition, increased storage behind hydropower dams also delays the onset of the flood pulse at the start of the wet season.

¹⁰ The Mekong River Commission refers to the Lancang-Mekong River/Basin as the Mekong River/Basin or Mekong River System, composing of two parts: the Upper Mekong River/Basin (in China) and Lower Mekong River/Basin.

¹¹ To simplify the analyses in this study, the dry season taken as the period from December to May, while the wet season taken as June-November.

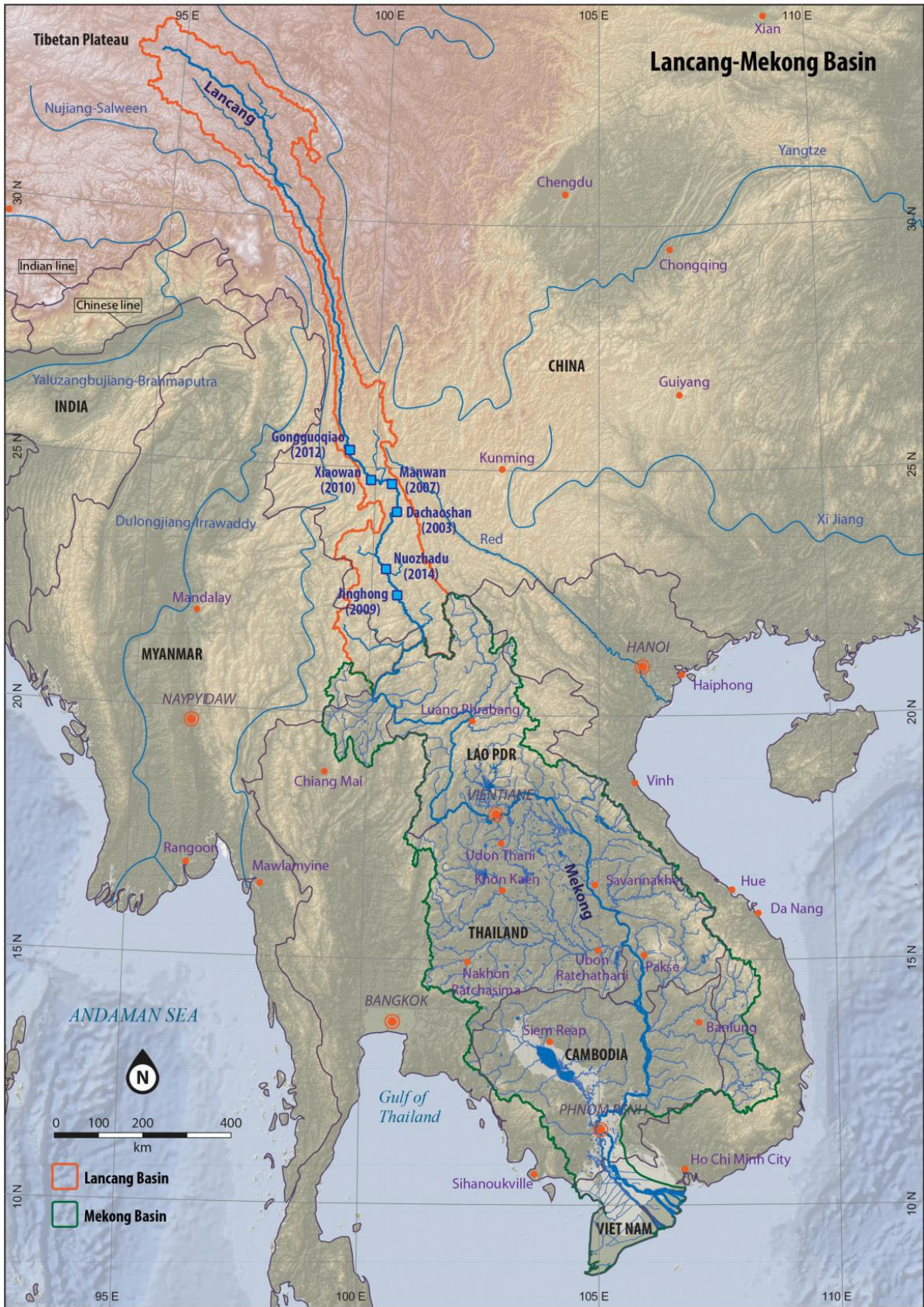


Figure 1. Map of the Lancang-Mekong Basin. The Lancang-Mekong Basin is the Mekong Basin in MRC documents, composed of two parts: the Upper Mekong Basin (Lancang Basin in China) and Lower Mekong Basin (MRC/MWR, 2016).

The Mekong has experienced several droughts over the last few decades, but since 2019 the Basin has suffered the most severe droughts on record (MRC, 2020a; MRC, 2021a). This resulted in the lowest water levels in over a century (Keovilignavong et al., 2021; Lovgren, 2019). Weatherby (2021) notes that the combined impacts of drought and alterations to the natural flow of the Mekong River from hydropower have affected the annual flood pulse in 2019 and 2020, which drives the Mekong's fisheries and provides sediments to the floodplains in the lower reaches of the river. Reduced rainfall in Cambodia dropped that country's electricity production by 30% (Weatherby, 2021). The Diplomat (Fawthrop, 2019; Hunt, 2019) reported that mass death of fish occurred during the drought due to the shallow water, high temperatures and low oxygen concentrations. That severe drought directly affected around 2.5 million people.

The impacts of the drought were particularly evident in the Tonle Sap Lake, Cambodia's inland lake, which experienced exceptionally low water levels impacting fisheries activities (Hunt, 2019; Kijewski, 2019). Citing a study by 'Eyes on Earth', Al Jazeera (Kijewski, 2019) reported that the water level in the Mekong River had dropped around five metres at the height of the drought. In addition, Reuters (2020) reported that the flows in the Mekong during the 2019 drought had dropped to the lowest levels in more than 50 years and carried less sediments, adversely impacting agriculture and fisheries.

The record drought of 2019 continued into 2020, causing the river levels to drop by two-thirds (The Hunt, 2020). The MRC Report on hydrological conditions in the LMB for January to July 2020 shows that 60% of the LMB Basin experienced a severe dry spell in July 2020 (MRC, 2020b). This drought was the most severe on record, including the catastrophic drought in 2016, which created economic losses of around 650 million USD and adversely affected the lives of 17 million people in the delta (Loc et al., 2021). Reduced freshwater inflows into the Delta means more seawater intrusion. Salinities in the delta during the 2019-2020 drought were higher than those noted in 2016 and entered as far as 50-130 km into the distributaries (Loc et al., 2021). The higher salinities severely affected agriculture and fisheries. In their study, Pokhrael et al. (2018) found that a greater than 20% reduction in the peak flood pulse near Stung Treng in Cambodia could potentially prevent the natural flow reversal in the Tonle Sap River.

As we will show later in this report, these conditions have persisted into the wet season of 2021. The ramifications of the lower volume and delayed monsoons, together with increases in the volume of the wet season flows that are stored behind hydropower dams, are therefore wide-ranging. The impacts on the people who depend on the river systems, the ecological functioning of the Mekong and Tonle Sap Great Lake, the people of the Delta and the regional economy are considerable. These impacts have been widely reported in the press, who have variously apportioned responsibility on the unprecedented drought, climate change, an *El Nino* event, and the impacts of storage in China's large reservoirs. It is therefore prudent to further investigate the causes of the low flows and to suggest potential measures to address these.

1.2 Objectives

In complex and large transboundary basins like the Mekong, with rapidly increasing levels of storage and no agreed drought operating rules, the reasons for the extreme low flows are complex. Drought can be meteorological and/or hydrological (Huang et al., 2017). The intensity of meteorological drought is measured by the rainfall anomaly and the duration of lower-than-normal rainfall. The intensity of hydrological drought is based on the impact of rainfall deficits on the overall water supply, including stream flow, reservoir and lake levels, and declining groundwater tables. Therefore, it is crucial to investigate the causes of the low flows and severe drought using all available data. Identifying the

causes of these low flows and the relative contributions of the different drivers of low flows is critical to decision making, water diplomacy, and future adaptation strategies.

Several separate studies of the recent low flows in the Mekong mainstream have been conducted, and various causes for the low flows have been identified as the primary drivers. However, the Mekong River Basin lies across the territories of 6 riparian Countries and lies in a geopolitically complex region of the world. Geopolitics may therefore have a role in shaping these study outcomes (Keovilignavong et al., 2021). These studies, particularly those that have raised concerns over the existing and planned infrastructure on the Mekong (Grunwald et al., 2021), need careful unpacking as they go to the heart of the MRC's *raison d'être* and its obligations towards its Member Countries.

This report, therefore, aims to provide a comprehensive, unbiased perspective on the drivers of the low flows over the last three years. This is done within the water diplomacy context of all riparian Countries, as well as the provisions of the 1995 Mekong Agreement. It then outlines, very briefly, some drought management measures that could be explored further.

2 Flows and the Functioning of the Mekong River System

2.1 Natural hydrological characteristics of the mainstream

The Mekong mainstream has typically been characterised by a single monomodal flood peak driven by the timing of the onset and end of the monsoon rains (Figure 2). This characteristic, and the definition of the wet and dry seasons, establish the way new projects are notified and discussed and how flows are maintained under the provisions of the 1995 Mekong Agreement¹².

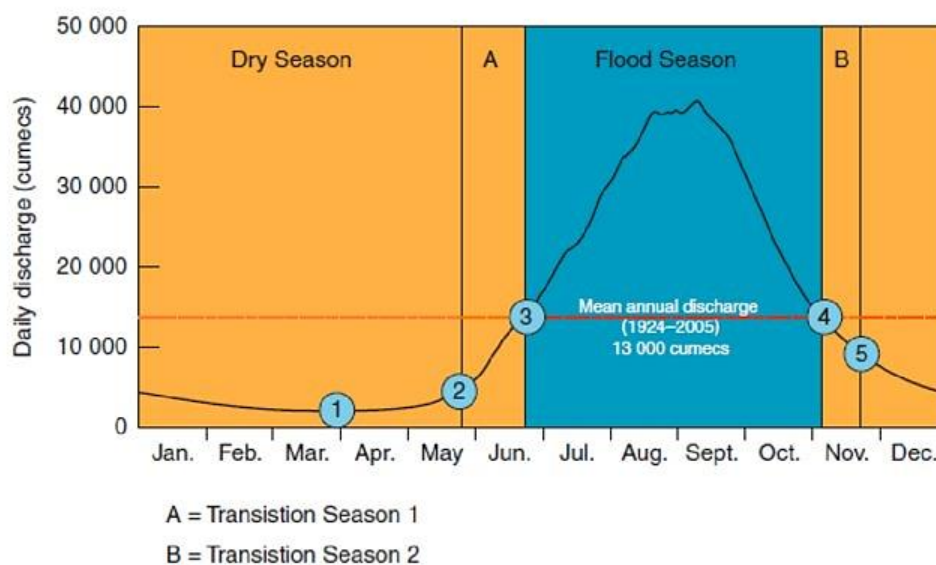


Figure 2. The monomodal flood peak characteristics of the Mekong mainstream (Adamson et al., 2009). In this proposal, the Dry Season and Flood Season are determined by the time when flow in the river crosses the long-term average. This was never formally adopted.

2.2 Changing hydrological characteristics

Developments in the Basin are changing the hydrological characteristics of the mainstream, a concept long understood by the MRC. These changes can be simplified as follows:

- With the onset of the rains, typically in May, June or July, the soils of the Basin start saturating. Runoff starts gradually increasing based on when the rains are falling.
- In catchments with storage, this storage first needs to fill up and start spilling before contributing to flows in the mainstream¹³.
- This delays the onset of the flood pulse at the start of the wet season and reduces the total volume of the wet season flows (Binh et al., 2020).
- This is also influenced by the timing and magnitude of the monsoon rains.
- The total active storage also influences the dry season flows in the following year as water is released through the turbines to maintain electricity supply and to comply with power purchase agreements.

¹² Formally: Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin, 5 April 1995.

¹³ Except if deliberate compensation releases are made before full supply levels are reached.

The following factors must therefore be considered when assessing the impacts on mainstream flows in any year (in no particular order):

- The total amount of active storage in the Mekong Basin – the more storage, the greater the delays in the first flood pulses, and the lower the wet season flows (Figure 3) (MRC, 2010).
- The runoff to storage ratios in the catchment areas above the storage, which influences the time it takes to fill them.
- The percentage of active storage at the start of the wet season. The lower the active storage at the start of the wet season, the greater the delays in the flood peaks.
- Whether any compensation releases are made before the reservoirs reach full supply levels.
- The timing and volume of the monsoon rains. Delays in the of the monsoons means the greater the delays in the flood pulse. Reduced rainfall means less runoff.

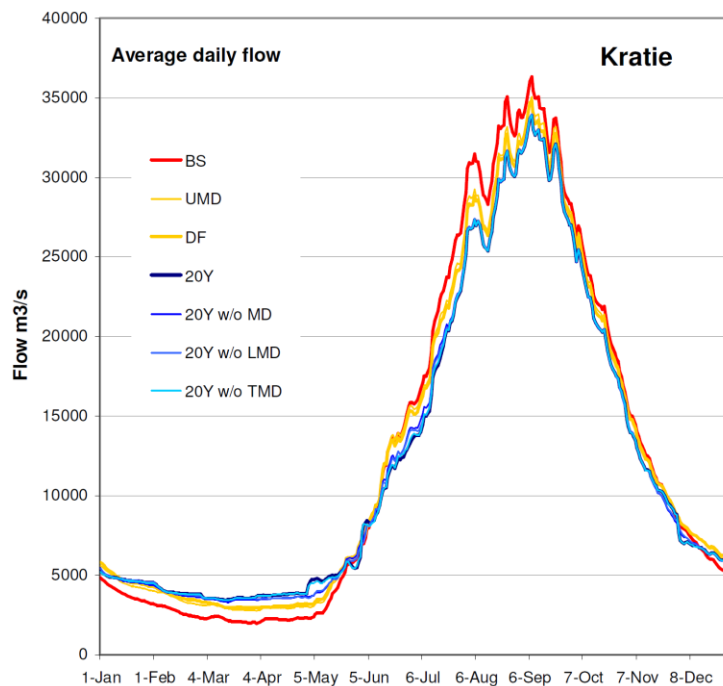


Figure 3. Expected changes in the mainstream flows with developments in the Basin.

Red Line: Baseline 1985-2000, Yellow Line: Developments up to 2015, Blue Line: Planned Developments up to 2030 (MRC, 2010).

The Tonle Sap Lake acts as a bellwether for the combination of these factors. When water levels in the Mekong at Phnom Penh Port rise above the levels in the Tonle Sap Great Lake at Kampong Luong, flows in the Tonle Sap River reverse, flowing from the Mekong into the Lake. This reverse flow typically contributes some 50% to the total inflows to the Lake, and the rest comes from the local catchments surrounding the Lake. If the Tonle Sap catchments have received less rain, a greater proportion of the volume of the Lake may come from the Mekong; if the Mekong wet season peak flows are lower, a greater proportion may come from the local catchments. If the local catchments receive early rains, it will take longer for the reverse flows to start.

The Tonle Sap Lake fills into the wet season, based on water level differences between the Lake and the Mekong, usually reaching its peak water levels in September/October. The duration and volume of the reverse flow period are driven by the total water level differences and varies considerably from year to year. As the water levels in the Mekong mainstream drop, the flow in the Tonle Sap River again reverses, flowing from the Lake into the Mekong. This process typically runs into February the following year and plays a vital role in maintaining lower salinity levels and providing water for irrigation in the

Delta. This phenomenon is recognised by the people of this region, who point to lower levels in the Tonle Sap Lake, upstream dams and increased dredging of the distributaries as the source of the higher salinity (Financial Time, 2021). Higher sea levels due to climate change will further complicate these salinity dynamics.

Fish abundance and diversity in the Great Lake and Tonle Sap River have also been positively linked to higher lake levels (see Annex A). In 2018, generally considered a wet year, higher lake levels contributed to high fish abundance and biomass, but since 2019 fish abundance and biomass has been declining. Given the natural variations in the monsoon rains, the Lake ecosystem will have some resilience to variable timing, duration and volume of the reverse flows and local catchment contributions. However, there may be a tipping point beyond which severe and lasting damage will occur.

3 Drought management in the 1995 Mekong Agreement

The 1995 Mekong Agreement, while not explicitly saying so, makes provision for drought management in Articles 5, 6 and 26. The underlying principle behind Article 5 (Reasonable and Equitable Use), Article 6 (Maintenance of Flows on the Mainstream), and Article 26 (Rules for Water Utilisation and Inter-Basin Diversions) of the 1995 Mekong Agreement is that during the wet season, there is enough water to satisfy the needs of all the Member Countries. But during the dry season, upstream abstractions (or diversions) of water could compromise downstream use. Radosevich (1995), in his comments on the negotiations leading up to the Agreement, highlights the wishes of the MRC Member Countries to minimise the need for interventions by the MRC within this context. The upshot of this aspiration was the need to define the extent of the 'wet' and 'dry' seasons and for different 'rules' or approach to apply to water resources management in these seasons.

Water use in the dry season would be subject to more rigorous consultation. The proposals for the definition of the wet and dry seasons outlined in Figure 2, i.e., the crossing points for the mean annual discharge, is just one of several suggestions tabled for discussion (MRC, 2008). Yet, despite these attempts to agree on the start and end times for the wet and dry seasons, these have still not been formalised. To date, this has been moot, as all the proposed projects on the mainstream have been year-round uses of water i.e., mainstream hydropower. However, as is clear from the analyses outlined in this report, drought and increasing storage in the Basin can delay the onset of the flood season when potentially different approaches would apply to the way new diversion/abstraction projects are notified and negotiated. This may become an increasingly important consideration as demands for water increase, droughts become more intense, and the total storage in the Basin increases (MRC, 2019b). The way these definitions are applied, if at all, will become critical to drought management proposals. The sub-sections below outline Articles 5, 6 and 26 provided for drought management through the Procedures for Notification, Prior Consultation and Agreement (PNPCA) and the Procedures for the Maintenance of Flows on the Mainstream (PMFM).

3.1 Notification, prior consultation and agreement (PNPCA)

Drought management operations in the LMB can be implemented through the 1995 Mekong Agreement and five MRC Procedures, especially the PNPCA by attaching conditions to new storage or abstraction projects that are made subject to prior consultation as provided for in Article 5.4.3 of the PNPCA.

Radosevich (1995), in his commentaries, notes that Article 5 on reasonable and equitable use, which outlines the conditions for when notification, prior consultation and agreement are applied, was the most difficult to agree. Foreign policy in all six nations riparian to the Mekong is founded on the principle of non-interventionism. This is a corollary to the right of territorial sovereignty held by each nation, which is expressed in Article 4 of the 1995 Mekong Agreement. Thus, the Member Countries spent some time negotiating the wording of Article 5 to strike the right balance between consultations and agreements *via* the MRC and simply informing the Commission of their planned measures.

The Agreement is unique in the way it balances this right to self-determination with the need to discuss and come to a consensus on transboundary matters. Principally, it differentiates the approaches to consultation and for managing flows on a hydrological (tributaries and mainstream), temporal (wet and dry season), and geographic (intra and inter-basin) basis (Figure 4).











Application of PNPCA Cooperation Processes			
Type of River	Season	Scope of water use	Required process
 Mainstream	 Dry	Inter-basin (from the Mekong basin to another basin)	 Specific Agreement
		Intra-basin (within the Mekong basin)	 Prior Consultation
	 Wet	Inter-basin (from the Mekong basin to another basin)	 Prior Consultation
		Intra-basin (within the Mekong basin)	 Notification
 Tributary	 Both	Both inter and intra-basin	 Notification

Figure 4. The different approaches to notification, prior consultation and special agreement outlined in Article 5 of the 1995 Mekong Agreement (MRC, 2018).

Under Article 5, all proposed projects on the tributaries are subject to notification only. While the Member Countries and the Secretariat can submit comments on notified projects (PNPCA Art. 4.3.2) there is no opportunity for consultation. Intra-basin projects on the mainstream in the wet season are also subject to notification only. However, the Technical Guidelines for the PMFM indicated that the notifying party should outline how the flows in the mainstream would be maintained under the PMFM for planning purposes (MRC, 2021b).

In the dry season, projects on the mainstream would be made subject to prior consultation. This provides the opportunity to discuss operating rules that could be applied to diversion/abstraction projects as part of drought management operations. However, where low flow conditions extend into the ‘wet season’ as was the case in 2019, 2020 and 2021, there would be no opportunities for these discussions. Despite the expansion of dry season irrigation in the Mekong Delta, none of these projects has been notified or made subject to prior consultation. Thus, there are no agreed drought operations measures to reduce abstractions in drought.

Inter-basin projects on the mainstream in the wet season are also subject to prior consultation, and hence the opportunity to incorporate drought operating rules that may specify the flow conditions under which diversions may have to be reduced or stopped. Inter-basin diversions from the Mekong Basin would require a special agreement (Figure 4).

3.2 Maintaining flows on the mainstream (PMFM)

Article 6 of the 1995 Mekong Agreement also provides for proactive low flow management by the Member Countries, with the notable exception of ‘severe droughts or floods’. Quibell and colleagues (2013) note, in this context, that agreement of what constitutes a ‘drought’ has often been difficult to finalise. Indeed, the need to manage flows by reducing diversions of water in severe drought may be

the exact time these measures are needed¹⁴. Nonetheless, in Article 6A the Parties agreed to maintain an acceptable minimum monthly flow in the dry season, and in Article 6B an acceptable natural reverse flow in the Tonle Sap Lake in the wet season¹⁵ (Figure 5).

Radosevich (1995) indicates that the intention here was:

“... that the use of this [acceptable minimum monthly] flow level is for projections by the Committee (or a sub-committee) that would probably begin sometime in October or November when there is a sharp decline in the hydrograph curve, to determine the amounts of water available (surplus) for sharing above the acceptable minimum monthly natural flow. And, that the Committee will have the current years data and trend upon which to make this determination with the ability to make adjustments or refinements on such calculations proceeding into the dry season months. That these flows during the dry season months are relatively constant as indicated by available data, particularly relative to the enormous wet season discharges, should clearly indicate to the riparian where the priorities on ‘cooperation’ ought to be placed for the greatest ‘payoff’ in mutual benefits to each.”

The maintenance of flows in the mainstream was therefore intended to be a dynamic process of sharing water above a minimum flow requirement based on forecasting dry season flows – known in the Agreement as surplus water (see Article 26).






Criteria on Water Flow				
River	Season	Type of Flow to maintain	Flow Assessment Criteria	
			for Monitoring	for Planning
 Mekong River	 Dry	Minimum monthly flow	A set of minimum daily flow	A set of minimum monthly flow
	 Flood	Maximum daily peak flow	A set of maximum daily flow	A set of maximum monthly flow
 Tonle Sap River	 Wet	Reverse flow	A range of historical daily flow at Prek Kdam	A range of seasonal flow at Kratie

Figure 5. Criteria on water flow with the seasons defined in the PMFM (MRC, 2018).

¹⁴ The ‘except in cases of severe drought’ wording is intended to indicate that if the Member Countries do not have sufficient water because of very low rainfall, they can’t be expected to release it. This principle is particularly relevant to the discussions in this report.

¹⁵ Article 6C deals with flood management and is not covered here.

3.3 A shifting emphasis

The 1995 Mekong Agreement has been described as an ‘agreement to agree’. Agreement on the definitions of the wet and dry seasons, the minimum monthly flows, the points at which these flows would apply, and the criteria for determining surplus water was deferred to the development of the *Rules for Water Utilisation and Inter-basin Diversions* under Article 26 of the Agreement.

Ultimately, these ‘Rules’ became the five MRC Procedures, and the minimum monthly flows in the PMFM became targets for monitoring and reporting rather than a trigger for active management actions. The emphasis placed on the implementation of the PMFM and the PNPCA as potential drought management tools has therefore shifted towards monitoring and reporting rather than operational management. This appears to reflect a balance between sovereignty and joint management that the Member Countries are currently more comfortable with.

However, the Siem Reap Declaration of 2015, the Basin Development Strategy 2021-2030 and MRC Strategic Plan 2021-2025 have recognised the need for an operational management approach to droughts and floods. Section 7 of this Report outlines some initial considerations in this regard.

4 Methodology and Data

4.1 Scope of study

The study has the following scope:

- **Temporal scale:** January 2018 to December 2021 – focusing on the 2019, 2020 and 2021 wet and dry seasons.
- **Spatial scale:** Meteorological and hydrological observations on the Mekong mainstream, the whole Basin, and the Tonle Sap Lake, including those data available for Upper Mekong Basin.

4.2 Hydrological datasets and stations

The MRC Data and Information Services provide near real time water level monitoring on the mainstream and main tributaries of the Mekong: <https://portal.mrcmekong.org/monitoring/river-monitoring-telemetry>. The current analyses are based on 13 key stations on the Mekong River and Tonle Sap River/Lake, whose hydro-geographical features are described in Table 1.

The ‘normal’ hydrological conditions (max, min and average) for 2008-2017 are compared to daily flows in 2018-2021. Table 1 summarises the characteristics of the hydrological stations and their data availability, and Figure 6 shows the location of these stations. Jinghong is the only hydrological station on the mainstream of the Upper Mekong River, for which data were available. Only flood season (June-October) data were shared at this station from 1998, but year-round data has been shared from 2021.

Table 1. Data availability for the Mekong mainstream and Tonle Sap Lake stations.

No	Station	River	River kilometre	Hydro-geographical features	Data availability
1	Jinghong (China)	Lancang/ Mekong	2,707 km	Only hydrological station on Lancang River	1998-2021 (wet season, 2021 full year)
2	Chiang Saen (Thailand)	Mekong	2,364 km	Recognised as transboundary station	1961-2021
3	Luang Prabang (Lao PDR)	Mekong	2,010 km	Key station upstream of Xayaburi	1960-2021
4	Nong Khai (Thailand)	Mekong	1,549 km	Key station downstream of Xayaburi	1970-2021
5	Nakhon Phanom (Thailand)	Mekong	1,221 km	Key station downstream of Vientiane	1973-2021
6	Mukdahan (Thailand)	Mekong	1,128 km	Upstream of Kong-Chi-Mun confluence	1960-2021
7	Pakse (Lao PDR)	Mekong	866 km	Downstream of Kong-Chi-Mun confluence	1960-2021
8	Stung Treng (Cambodia)	Mekong	683 km	Transboundary flow monitoring for Lao PDR and Cambodia	1960-2021
9	Phnom Penh Port (Cambodia)	Tonle Sap	-	Key station for reverse flow to the Tonle Sap Lake	1960-2021
10	Prek Kdam (Cambodia)	Tonle Sap	-	Key station for reverse flow to the Tonle Sap Lake	1960-2021
11	Kampong Luong (Cambodia)	Tonle Sap Lake	-	Key station for reverse flow to the Tonle Sap Lake	1999-2021
12	Tan Chau (Viet Nam)	Mekong	-	Transboundary flow monitoring for Cambodia and Viet Nam	1980-2021
13	Chau Doc (Viet Nam)	Bassac	-	Transboundary flow monitoring for Cambodia and Viet Nam	1980-2021



Figure 6. Location of key hydrological stations for flow monitoring on the Mekong mainstream.

4.3 Precipitation data and drought Indexes

Monthly rainfall, rainfall anomaly and drought index data for the LMB were sourced from the MRC’s Regional Flood and Drought Management Center (RFDMC).

The accumulated monthly rainfall maps and monthly rainfall anomaly maps for the LMB for 2018, 2019, 2020 and 2021 are provided in Annex B and Annex C. The Standardised Precipitation Index (SPI) and the Combined Drought Index (CDI) maps are presented in Annex D.

4.4 Storage data

The volume of water stored in hydropower reservoirs across the whole Basin was also sourced from the Mekong Dam Monitor (MDM, 2021). Table 2 shows the storage characteristics for categories used on the MDM site, while Table 3 reflects these characteristics for each riparian country.

Table 2. The categories of large dams used on the Mekong Dam Monitor site, the total number of dams in each category, and the total active storage available* (MDM, 2021).

Category	Number of Dams	Estimated total active storage
MDM* Mainstream Dams	13	24.968 km ³
MDM* Tributary Dams	15	13.085 km ³
EDL** Wholly Owned Dams	10	5.444 km ³
EGAT*** Dams	7	3.299 km ³
Total	45	46.796 km ³

* Active Storage = Water that can be released downstream.

** Hydropower Dams owned by Électricité du Laos.

*** Hydropower Dams owned by the Electricity Generating Authority of Thailand.

It is crucial to note that the storage levels on the MDM website are based on ALOS satellite imagery. ALOS data have a vertical error margin ranging from about 2 m (Bayik et al., 2017) to some 5 -10 m (Santillan, 2016), which will introduce errors in storage volumes. However, the accuracy is sufficient to determine ‘changes in the patterns’ of storage in the Mekong Basin, which is used for this analysis.

There are 45 *large reservoirs* in the Mekong Basin, the majority of which (21) lie in Lao PDR. However, by far the largest proportion of the total storage lies in the UMB (56%), followed by Lao PDR (32.7%), and then Thailand with 7.5%. Smaller volumes of active storage lie in Cambodia and Viet Nam. The total active storage in the Mekong Basin is about 10% of the MAR. This limits drought management through storage to seasonal or monthly actions to restore flows as per the PMFM (see Section 6).

Table 3. Estimated total active storage in each riparian country (excluding Myanmar) (MDM, 2021).

Country	Number of Dams	Estimated total active storage	% active storage	% of Mekong MAR
Cambodia	1	1.037 km ³	2.3	0.22%
China	11	24.561 km ³	56.0	5.17%
Lao PDR	21	14.357 km ³	32.7	3.02%
Thailand	7	3,299 km ³	7.5	0.69%
Viet Nam	5	0.607 km ³	1.5	0.13%
Total	45	43.861 km³	100	9.23%

5 Analysis of the Results

5.1 Mainstream hydrology

The daily discharge characteristics of the Mekong mainstream are presented in Figure 7 and Figure 8. More detailed analyses of mainstream hydrology, including daily water level characteristics, are given in Annex E. The maximum, mean and minimum historical flows for 2008-2017 and flows for the years 2018, 2019, 2020 and 2021 are depicted.

Table 4 presents the differences in the wet and dry season accumulated flows, versus the average accumulated flows of 2008-2017. Table 5 expresses this as a percentage. A pattern of higher dry season flows and lower wet season flows remains clear from the observed flow at the mainstream stations (Table 5).

Figure 7 and Figure 8 reflect the combined influence of the factors listed in Box 1. The influence of the hydropower dams in the UMB is evident in the inflows to the LMB at Chiang Saen. Wet season flows tend to be lower, while dry season flows tend to be higher. These flow anomalies are less evident with increasing distance downstream, where the effects of LMB tributary inflows moderate the effects of the storage in the UMB. Figure 9 and Figure 10 show accumulated flows for 2018-2021 at mainstream stations for the dry and wet seasons, respectively.

In 2018, generally considered a wet year, all stations tend towards the maximum flows for wet and dry seasons recorded for 2008-2017, except at Chiang Saen. Although the first flood pulse delays are evident at all the stations, this was much more noticeable in 2019, 2020 and 2021. The flow peaks in 2018, downstream of Chiang Saen, are at least as high as the maxima for the 2008 to 2017 period. However, the duration of the higher flow period has reduced from about five months (June to October) to around four months (July to October) in all the years studied (Figure 7 and Figure 8).

The flow patterns in the first half of 2019 follow the expected pattern of higher-than-normal dry season lows, but the total volume of the wet season flow is considerably lower in 2019, 2020 and 2021. Downstream of Nong Khai, and particularly at Pakse and Stung Treng, there were short duration peaks in flow in September and October in 2019 and 2020.

The total flow 'deficit' in the wet season, determined from the difference between the average flows from 2008-2017 and the flows in the drought years, also increase downstream (Table 4). However, there are short-duration wet season flow peaks at the stations downstream of Luang Prabang¹⁶ further downstream in all three years. This suggests an increasing deficit in flows further downstream, which can only occur if the LMB tributary inflows were also lower-than-normal in the drought years. Table 4 shows that the accumulated flow over the 2019 wet season and Chiang Saen was 28.5 km³ lower than average, whereas the deficit at Stung Treng was 90.8 km³. This pattern was repeated in 2020 and 2021.

Box 1: The main factors affecting flow in the Mekong mainstream.

- The total amount of available storage in the Basin over the year.
- The ratio of the upstream catchment size.
- The total volume of storage at the start of the wet season.
- The timing and volume of the southeast Asian Monsoon.

¹⁶ Flows at Luang Prabang from December 2019 can be ignored as the station was drowned by the backwaters from the Xayaburi Hydropower Project. The backwater effect can be seen in Annex E, Figure E-1[3].

In summary...

- Inflows to the LMB (at Chiang Saen) in the drought years trended below the lowest records from 2008 to 2017. This was particularly evident in the wet season. This trend persisted through the whole Mekong mainstream.
- Wet season flows at all stations trend lower and for shorter periods in 2019, 2020 and 2021 than historical flow patterns.
- The total flow deficit in the wet season increases downstream, and the 'deficit' in total wet season flows at Chiang Saen is a fraction of that at Stung Treng.
- There are short duration wet season flow peaks further downstream in all three years.
- While 2019 had higher-than-normal dry season flows. The trend of lower-than-normal dry season flows continued into 2020 and 2021.

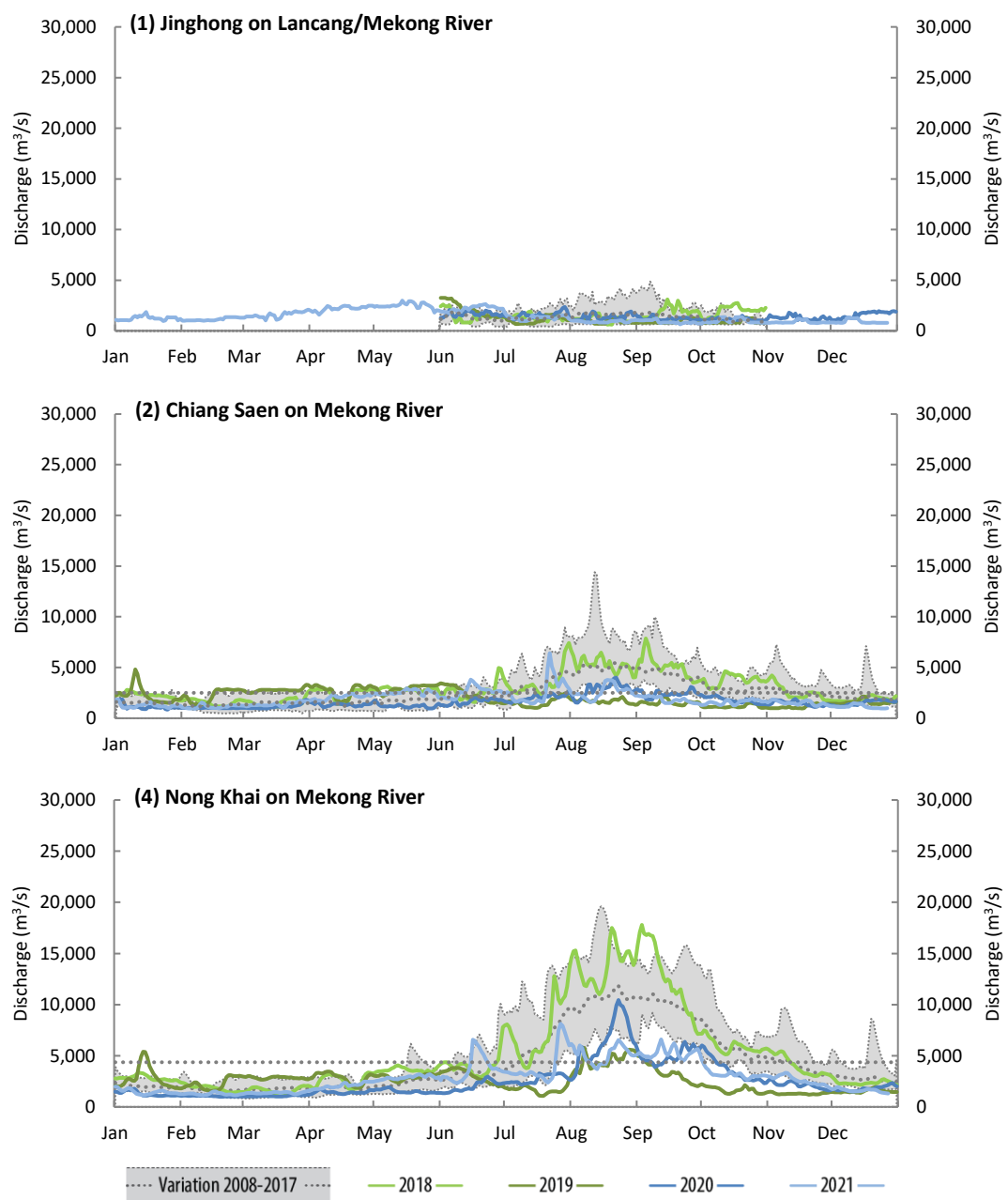


Figure 7. Characteristics of discharge of the Mekong mainstream at (1) Jinghong, (2) Chiang Saen, (4) Nong Khai, compared to conditions of 2008-2017. See location in Figure 6.

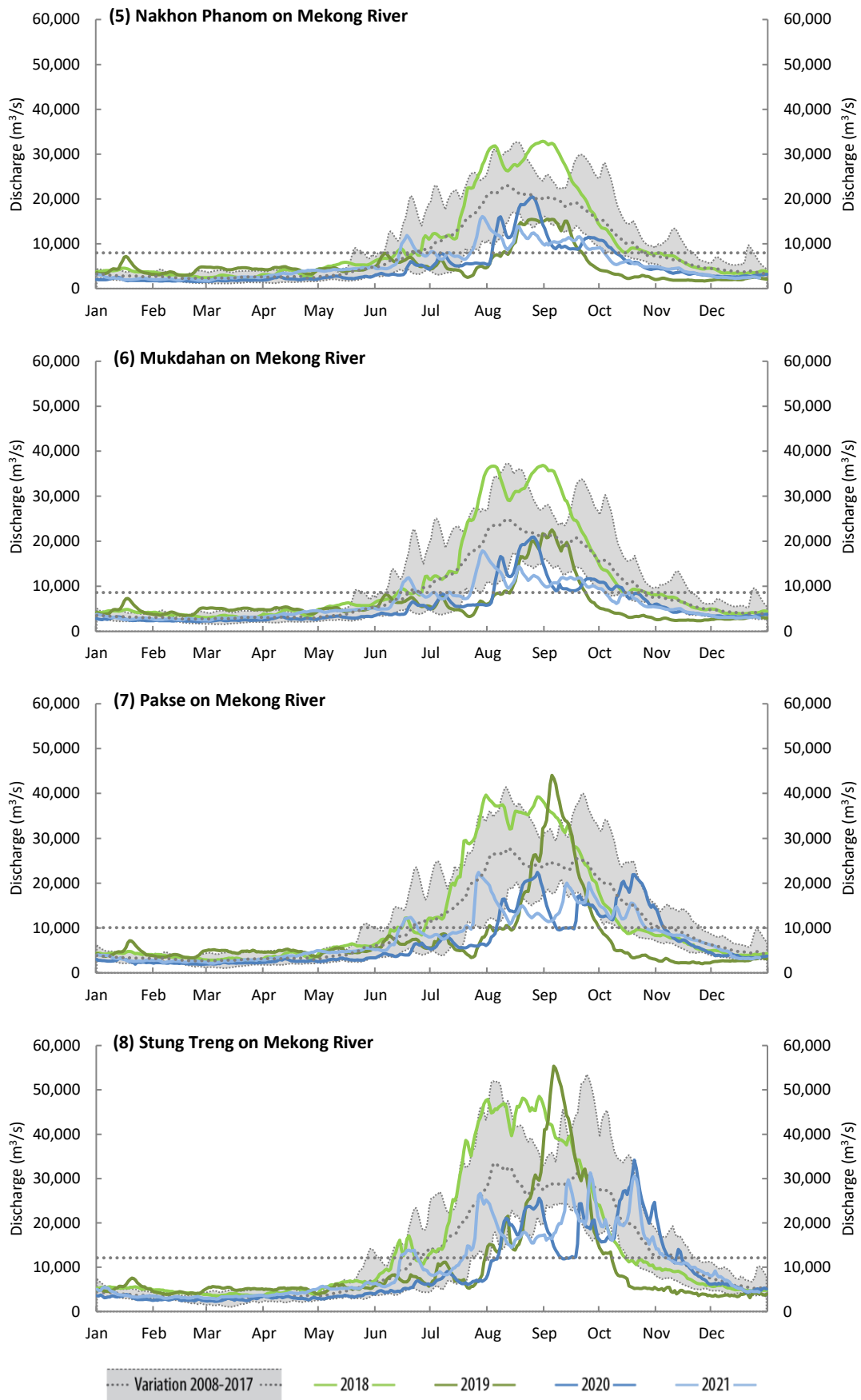


Figure 8. Characteristics of discharge of the Mekong mainstream at (5) Nakhon Phanom, (6) Mukdahan, (7) Pakse and (8) Stung Treng, compared to conditions of 2008-2017. See location in Figure 6.

Table 4. The difference in accumulated flows at mainstream stations for the wet and dry seasons of 2018-2021, versus the average accumulated flows of 2008-2017.

Volume (km ³)	2018		2019		2020		2021	
	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
Chiang Saen	7.85	6.91	13.57	-28.50	-5.62	-21.38	0.85	-19.73
Nong Khai	6.43	21.52	9.35	-64.05	-11.82	-47.11	-4.10	-41.62
Nakhon Phanom	10.99	48.00	17.66	-105.95	-14.57	-84.52	-1.40	-78.06
Mukdahan	12.54	58.01	18.80	-97.82	-10.96	-87.71	0.38	-80.00
Pakse	7.38	45.63	13.53	-94.18	-17.29	-91.82	-3.07	-75.54
Stung Treng	12.36	64.29	15.03	-90.80	-15.36	-99.63	2.55	-68.46

Table 5. The percentage difference between accumulated flows and average of 2008-2017.

Percentage (%)	2018		2019		2020		2021	
	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
Chiang Saen	131	113	154	46	77	60	103	63
Nong Khai	120	121	129	39	64	55	87	60
Nakhon Phanom	123	123	137	48	69	59	97	62
Mukdahan	123	127	135	55	80	60	101	63
Pakse	113	117	124	64	70	65	95	71
Stung Treng	119	120	123	71	76	69	104	78

Note: Figures over 100% indicate higher-than-normal flows, those below 100% indicate lower-than-normal flows.

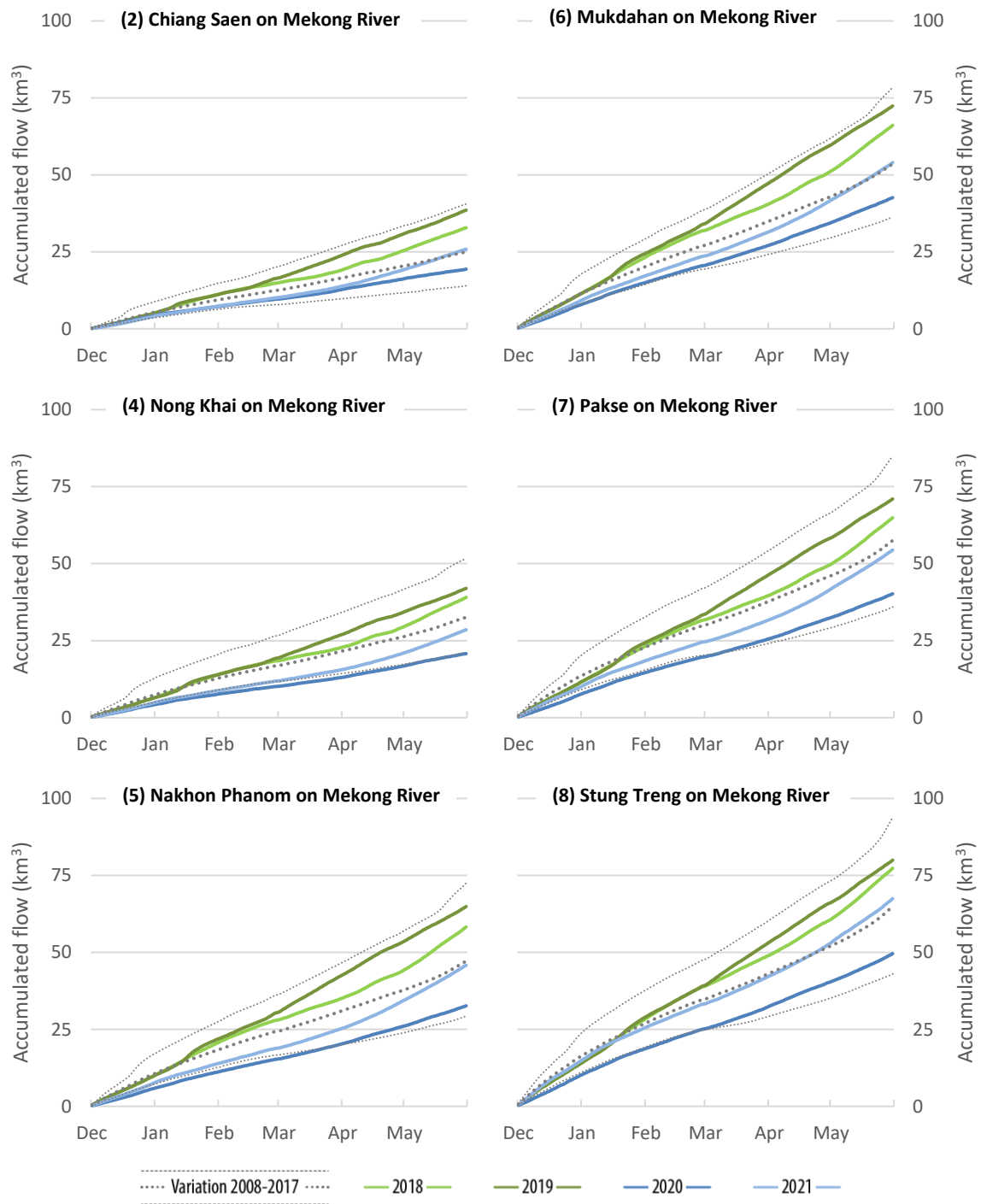


Figure 9. Accumulated flows at mainstream stations for the dry seasons of 2018-2021. See location in Figure 6.

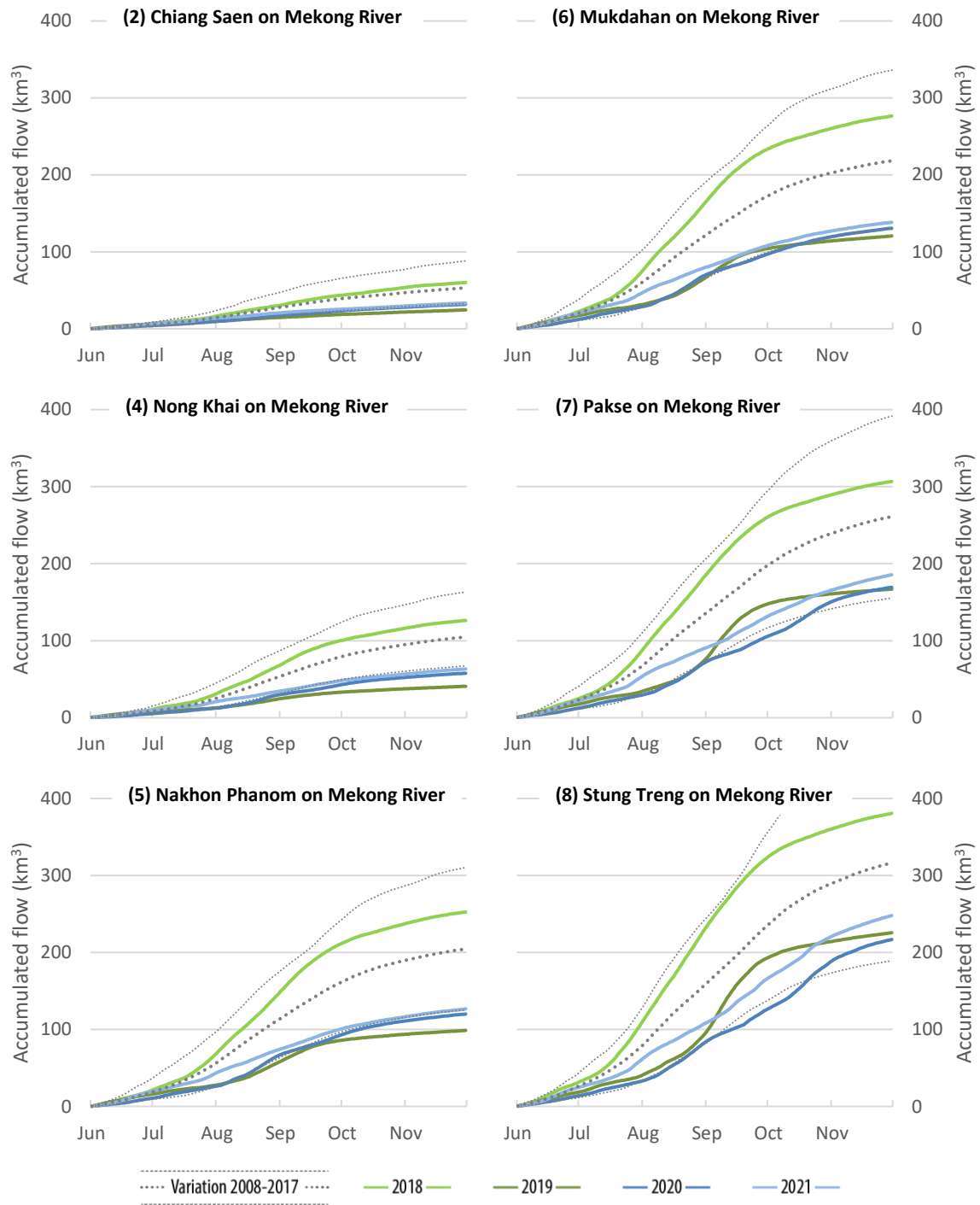


Figure 10. Accumulated flows at mainstream stations for the wet seasons of 2018-2021. See location in Figure 6.

5.2 Reverse flows into the Tonle Sap Lake

Water level data for Phnom Penh Port at the confluence of the Mekong and Tonle Sap Rivers, Kampong Luong in the Tonle Sap Great Lake, and for the inflows into Viet Nam at Tan Chau and Chau Doc on the Mekong and Bassac Rivers, respectively, are presented in Figure 11.

Historically, water levels in the Mekong River started rising from mid-May to October as the effects of the upstream rainfall and flows reach Phnom Penh (Figure 11[9]). At this time, the water levels in the Lake are lower than in the Mekong, and the Mekong water flows into the Lake. By October, the Lake reaches its full capacity, and water levels in the Mekong start to drop. Water then flows from the Lake to the Mekong River, contributing to increased flows into Viet Nam up to March/April the following year. This reverse flow provides a vital ecological service to both Cambodia and Viet Nam and is critical to the countries economies. However, only about 50% of the inflows to the Great Lake are from the Mekong River (Matti et al., 2014). As such, the pattern and timing of the reverse flow are also affected by local rainfall and irrigation demands in the Tonle Sap Lake/River catchment.

Box 2: The factors affecting return flows into the Tonle Sap Lake and flows into the Delta into the following dry season.

- The water levels differences between the Lake and Mekong Mainstream.
- The duration of this disparity.
- Rainfall and runoff from the Tonle Sap local catchment.
- Dredging and other factors affecting the river channel morphology.

Figure 12 shows that the reverse flows in 2019, 2020 and 2021 were delayed, starting only in late June or early July. Peak accumulated reverse flow in these years was also delayed and lower-than-normal. The pattern of the Lake water levels in 2019, 2020 and 2021 are also very low (Figure 11[11]). This may have had an adverse impact on fish abundance and biomass in 2019, 2020 and 2021 (Annex A). The reduced Lake volumes are also likely to be the primary driver behind the problems reported by the people in the Delta in February and March.

The total reverse flow volumes, on which the PMFM for Article 6B are based, have also trended lower since 2019, with the total reverse flows in 2020 and 2021 lying at 58% and 51% of the average total reverse flow volume of 2008-2021 and are the lowest and second lowest since 2008. However, the 2019 total reverse flow volume is close to the average of 2008-2021 (Table 6).

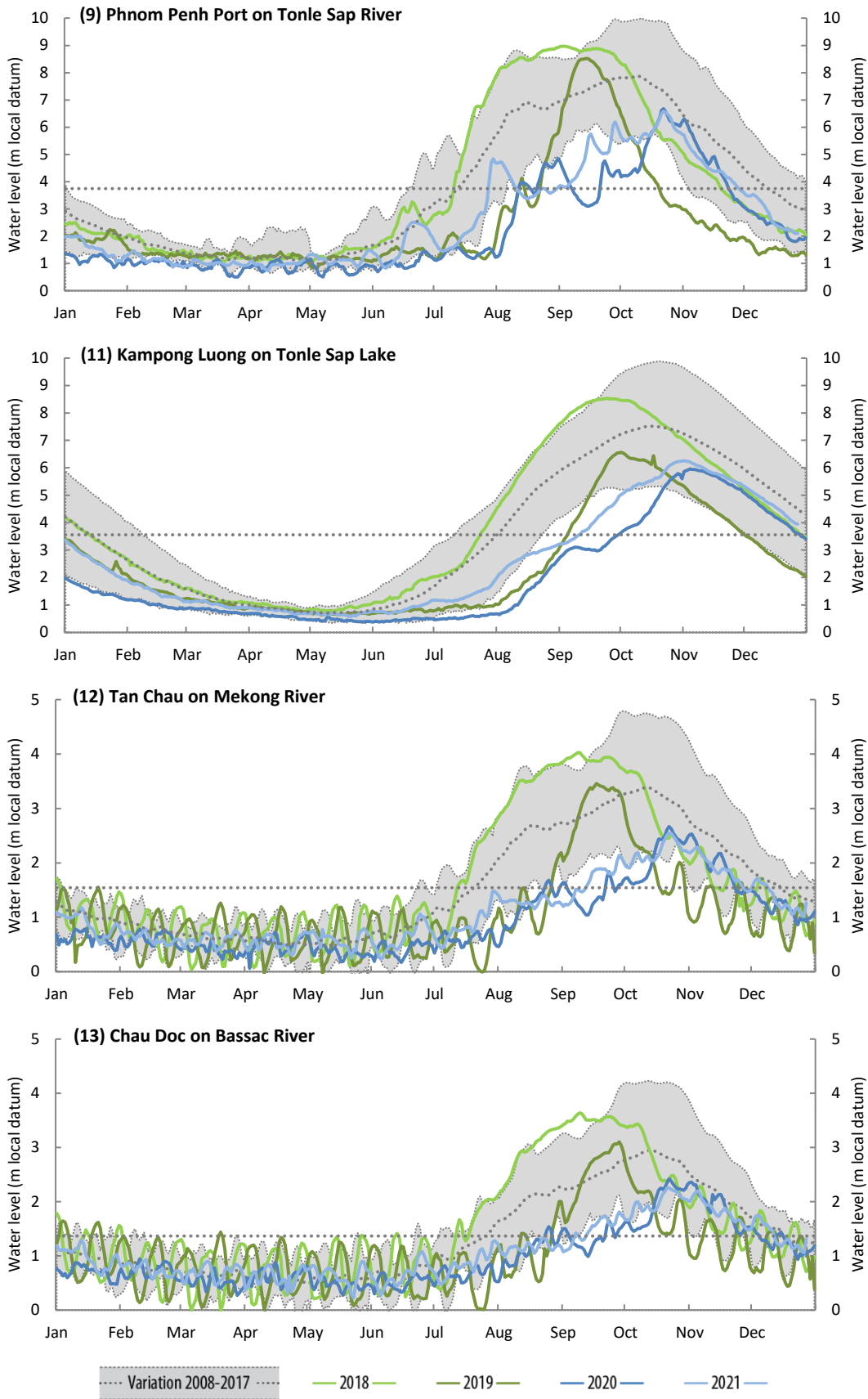


Figure 11. Characteristics of water level of the Tonle Sap Lake and Delta at (9) Phnom Penh Port, (11) Kampong Loung, (12) Tan Chau and (13) Chau Doc, compared to conditions of 2008-2017. Tan Chau and Chau Doc are affected by the spring and neap tides in the dry season. See location in Figure 6.

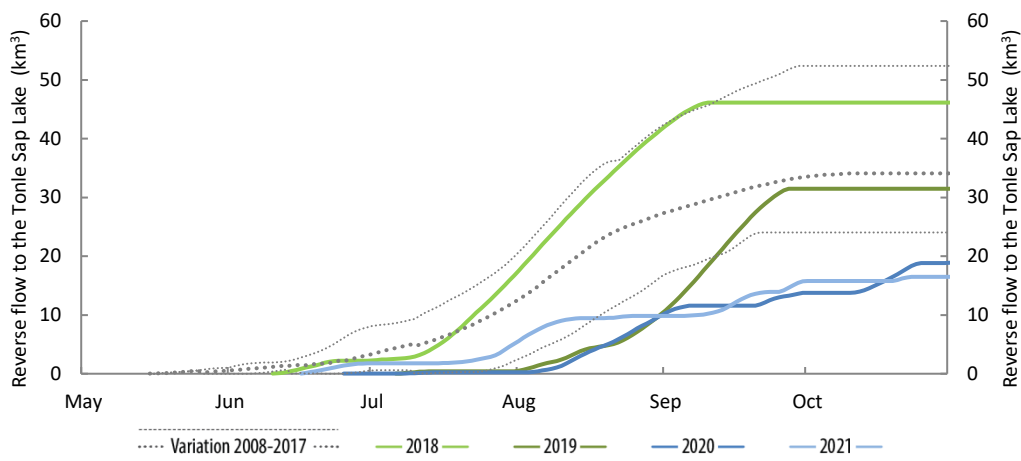


Figure 12. Characteristics of accumulated reverse flows to the Tonle Sap Lake for 2018-2021, compared to the minimum, maximum and average of 2008-2017.

Table 6. Summary of accumulated reverse flows to the Tonle Sap Lake for 2008-2021.

Year	Start date	End date	Duration (day)	Reverse flows (km ³)	Change (km ³ /day)
2008	16 May ^{L***}	30 Sep	138 ^{H***}	35.51	0.26 ^{L*}
2009	26 May ^{L**}	10 Oct	138 ^{H***}	37.66	0.27
2010	10 Jul ^{H***}	23 Oct ^{H*}	106	29.40	0.28
2011	30 May	29 Sep	123	52.36 ^{H***}	0.43 ^{H**}
2012	27 May	20 Sep	117	33.29	0.28
2013	17 Jun	04 Oct	110	38.28 ^{H*}	0.35
2014	14 Jun	07 Sep ^{L**}	86 ^{L**}	36.31	0.42 ^{H*}
2015	25 Jun ^{H*}	21 Sep	89	24.06 ^{L*}	0.27
2016	21 Jun	28 Sep	100	26.94	0.27
2017	26 May ^{L*}	20 Aug ^{L***}	87 ^{L*}	27.28	0.31
2018	10 Jun	10 Sep ^{L*}	93	46.12 ^{H**}	0.50 ^{H***}
2019	06 Jul ^{H**}	27 Sep	84 ^{L***}	31.46	0.37
2020	25 Jun	26 Oct ^{H***}	124 ^{H*}	18.85 ^{L**}	0.15 ^{L**}
2021	16 Jun	23 Oct ^{H**}	130 ^{H**}	16.50 ^{L***}	0.13 ^{L***}
Mean	12 Jun	28 Sep	109	32.43	0.31
Min	16 May	20 Aug	84	16.50	0.13
Max	10 Jul	26 Oct	138	52.36	0.50

Note: Colour code is based on the ranking system where the percentile is defined as the percentage of values found under the specific values, i.e., 'blue' represents the values higher or equal to 80 percentile and 'red' indicates the values lower or equal to 20 percentile.

H*** is the first latest date or highest value; H** is the second latest date or highest value; H* is the third latest date or highest value.

L*** is the first earliest date or lowest value; L** is the second earliest date or lowest value; L* is the third earliest date or lowest value.

5.3 Changes in storage

The analysis of the storage behaviours over 2018 to 2021 was based on the six largest reservoirs in the Mekong Basin and used data from MDM (2021). In China, the Xiaowan and Nuozhadu Reservoirs hold 92% of the active storage¹⁷ in the UMB, and in Lao PDR, the Nam Ngum 1 and 2, Nam Theun 2 and Theun Hinboun Expansion, which make up 89% of the active storage¹⁸ in Lao PDR. Together these reservoirs make up 81% of the total active storage in the Mekong Basin and hence potentially hold the best opportunities for drought management.

Figure 13 illustrates the layout of the Lancang Cascade, showing the upstream Xiaowan and the downstream Nuozhadu Reservoirs. All four reservoirs selected for the Lao PDR are on left bank tributaries, downstream of the Nong Khai and upstream of the Nakhon Phanom. They, therefore, influence flows downstream of Nong Khai.

Box 3: The factors affecting changes in storage.

- The disparity between inflows and outflows (including evaporative losses).
- Inflows are affected by the rainfall runoff over the upstream catchment, as well as the operations of any upstream reservoirs.
- The outflows are affected by power demands and the requirements of any Power Purchase Agreements, as well as spillages or deliberate releases to the downstream river.
- Operators who hold back storage to minimise the risks to generation in the upcoming months.

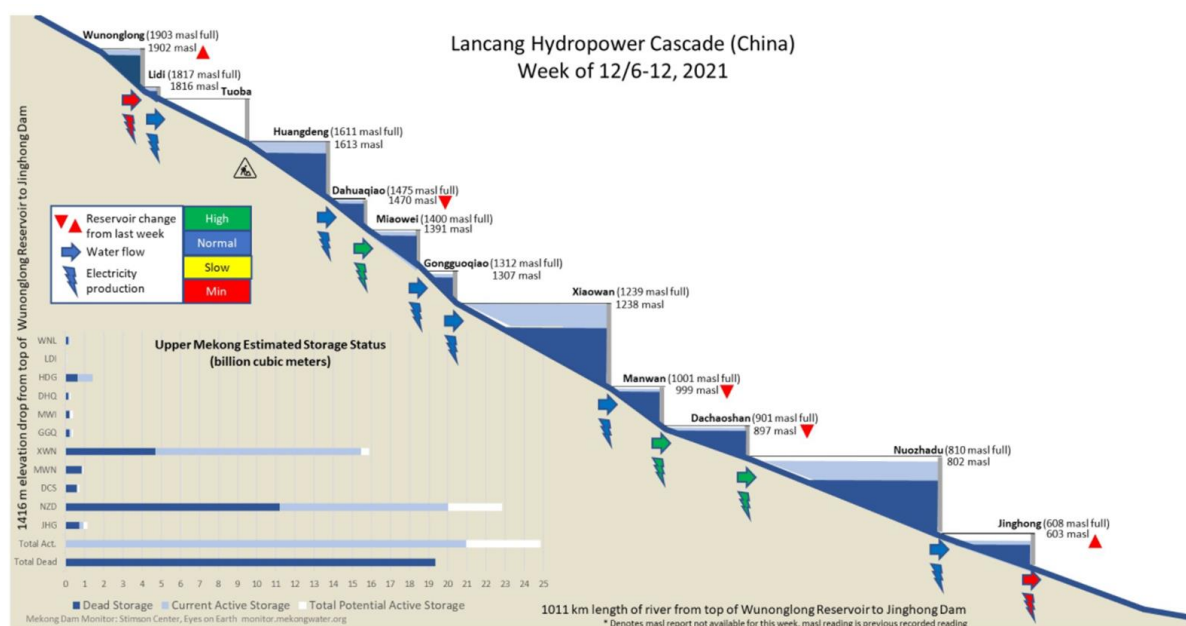


Figure 13. The Configuration of the Lancang Cascade Hydropower Projects (MDM, 2021).

¹⁷ Estimated total storage for Xiaowan is 15.884 km³ (estimated active storage: 11.174 km³ and estimated dead storage: 4.710 km³) and Nuozhadu is 22.848 km³ (estimated active storage: 11.358 km³ and estimated dead storage: 11.490 km³) (MDM, 2021).

¹⁸ Estimated active storage for Nam Ngum 1 is 4.400 km³. Estimate total storage for Nam Ngum 2 is 4.757 km³ (estimated active storage: 3.010 km³ and estimated dead storage: 1.747 km³), Nam Theun 2 is 2.860 km³ (estimated active storage: 2.469 km³ and estimated dead storage: 0.392 km³), and Theun Hinboun Expansion is 3.080 km³ (estimated active storage: 2.935 km³ and estimated dead storage: 0.145 km³). Storage data on Nam Ngum 1 could not be sourced (MDM, 2021).

Figure 14 shows the annual storage pattern for the Xiaowan and Nuozhadu Reservoirs. These reservoirs typically slowly empty from February to June each year as water is released but is not replaced by dry season inflows at the same rate. In the upstream Xiaowan, this process reverses in July when the reservoir starts rapidly filling in the wet season. In Nuozhadu, this process starts a little later, in August, after the upstream reservoirs start filling. Usually, these reservoirs are back close to their full active storage levels by October (Figure 14). This was not the case in 2019 when both reservoirs did not reach the levels seen in 2018. In 2019 both reservoirs together had a net gain in storage over the wet season of approximately 10 km³. In 2018, 2020, and 2021 the net gain in storage over the wet season was approximately 20 km³. The reduced storage in 2019 was particularly evident in the Nuozhadu Reservoir, which showed a very little pick up in storage into the wet season, despite the apparent releases from Xiaowan from November 2021 (Figure 14).

The lower storage at the end of 2019 had a knock-on effect into the dry season of 2020, with total storage starting at lower levels and only reaching ‘normal’ storage patterns in June/July. This suggests that the dry season energy output may have been reduced due to concerns over a repeat of the 2019 lower wet season inflows. Both reservoirs showed the normal filling patterns into the 2020 wet season. However, storage in December 2021 in Nuozhadu is some 3 km³ lower than the full supply.

To put these storage figures into some perspective, the average total reverse flow volume into the Tonle Sap Lake from 2008 to 2017 was about 34 km³. The total volume of water ‘held back’ in the two largest reservoirs in the UMB is consequently between ~30% (10 km³ in 2019) and ~60% (20 km³ in other years) of the average reverse flow volumes. This does not mean that the storage in the UMB reduces the reverse flow volumes by 60%; the figures are for comparison only.

The errors in storage volume estimate introduced by the vertical resolution of the satellite imagery, notwithstanding, it is evident that the two reservoirs stored less water in 2019 and that this carried over into 2020. But by the end of 2020, storage was closer to the usual levels. This did not reflect in ‘normal’ inflows into the LMB at Chiang Saen, which were still trending lower, although not as much as in 2019.

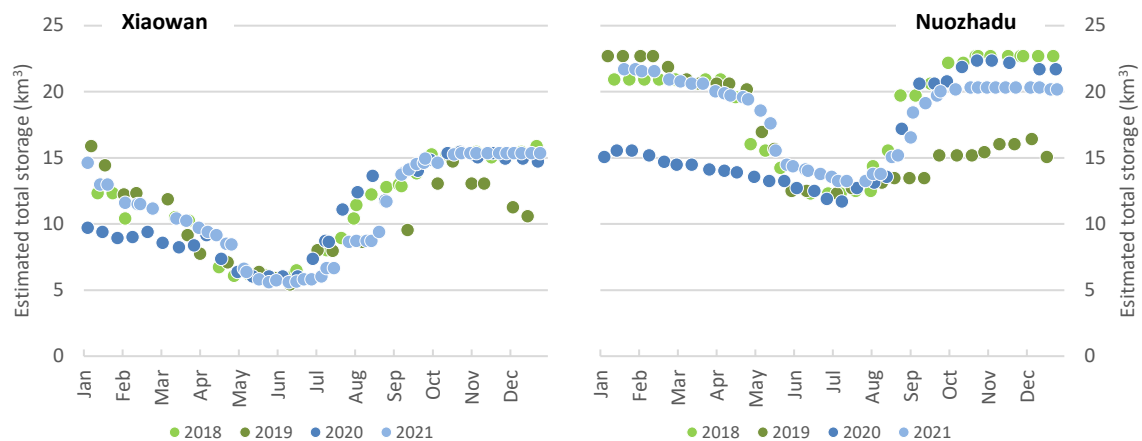


Figure 14. Storage behaviours for Xiaowan and Nuozhadu Reservoirs over the annual cycle for 2018 to 2021, suggested from satellite data (MDM, 2021). See location in Figure 13.

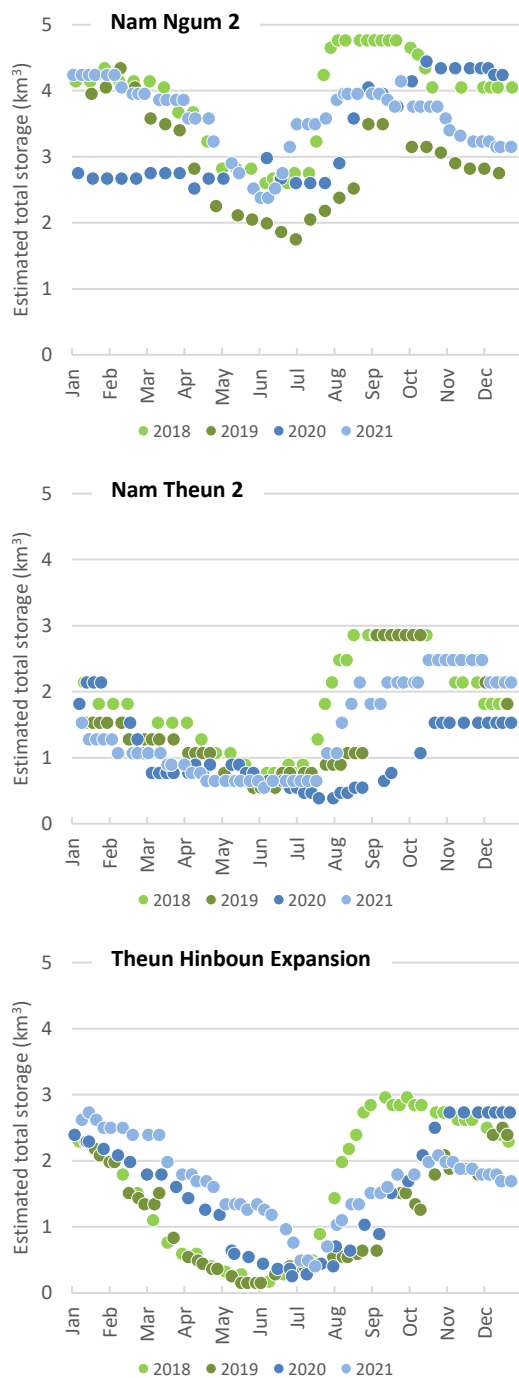


Figure 15. Storage behaviours for Lao PDR reservoirs over the annual cycle for 2018 to 2021, suggested from satellite data (MDM, 2021).

While it is difficult to draw firm conclusions without all inflow and outflow data and water balance calculations for all the storage, the following general deductions are possible:

- The total water ‘held back’ in the two largest reservoirs in the UMB in 2019 was less than in 2018, 2020 and 2021.
- This did not mean that *all* the inflow in the wet season of 2019 and the dry season of 2020 was retained, as releases were required to generate power.

The active storage in the four largest tributary reservoirs in Lao PDR is 57% of that in the two large reservoirs of the UMB. There are consequently fewer opportunities for meaningful drought management measures through compensation releases. The three reservoirs for which data were readily available show the same pattern of storage as those in the UMB (Figure 15). However, because these dams are smaller, the increases in storage with the start of the wet season are more marked. This is particularly evident in 2018 when the storage was close to full supply levels by August in Nam Ngum 2 and Nam Theun 2, and by September in Theun Hinboun. The drawdown after this would reflect both decreasing inflow and discharges through the turbines. This drawdown would contribute to the flows downstream of Nong Khai, which is evident in the hydrographs for the downstream stations (Figure 8).

The impacts of the drier-than-normal wet season in 2019 are evident in Nam Ngum 2, with the total storage at the end of 2019 being much lower than usual for that time of the year. Therefore, storage in the three large dams in Lao PDR started 2020 with an approximate 10% deficit over normal conditions. However, as for the storage in the UMB, by the end of 2020, storage levels were closer to normal conditions except in Nam Theun 2. Even in a ‘good year’, the net wet season storage in the three reservoirs, is about 6.5 km³ or 20% of the average reverse flow volume into the Tonle Sap Lake. Work by the MRC’s Initiative for Sustainable Hydropower (ISH) has shown that it would typically require the release of the total active storage in the LMB to reset the timing of the reverse flows each year (Krohn, *pers comm*).

- The lower storage at the end of 2019 carried over into the 2020 dry season. Operators would have been cautious over releasing additional water while facing the possibility of similar drought conditions in the wet season in 2020.
- Dry season contributions from storage to flows in the mainstream in 2020 would have been lower than in 2019 as a result. This is evident from the data presented in Table 4.
- By the end of 2020, total storage in the Basin was closer to normal levels, and in 2021 the dry season contributions to flow in the mainstream were closer to average conditions.
- Compensation releases to correct the *timing of the reverse flows* would have to start in June, when storage is at its lowest levels. This would pose a considerable risk to power production.
- Compensation releases to correct the *volume of the reverse flows* would be more viable in August when storage is closer to full supply levels.

5.4 Changes in rainfall patterns

Annex B reveals detailed assessment of the monthly rainfall over the LMB for 2018-2021 while Annex C presents the analyses of the monthly rainfall anomalies. In addition, monthly rainfall, Standardised Precipitation Index and Combined Drought Index Maps for the LMB are available in Annex D. Figure 16 presents the monthly total rainfall over the LMB for 2018-2021.

Box 4: The factors affecting changes in rainfall.

- Climate Change.
- The timing of the onset and end of the monsoon rains.
- The *El Nino - La Nina* phenomenon.

Figure 17 presents rainfall anomaly in August for 2018-2021, compared against the average of 2000-2020. This suggests that August¹⁹ 2019 was an exceptionally dry month in the UMB. Precipitation anomaly maps from MDM (2021) suggests that the UMB has had below-normal to normal precipitation over most of its area since 2019.

¹⁹ August is taken as indicative of the early wet season rains.

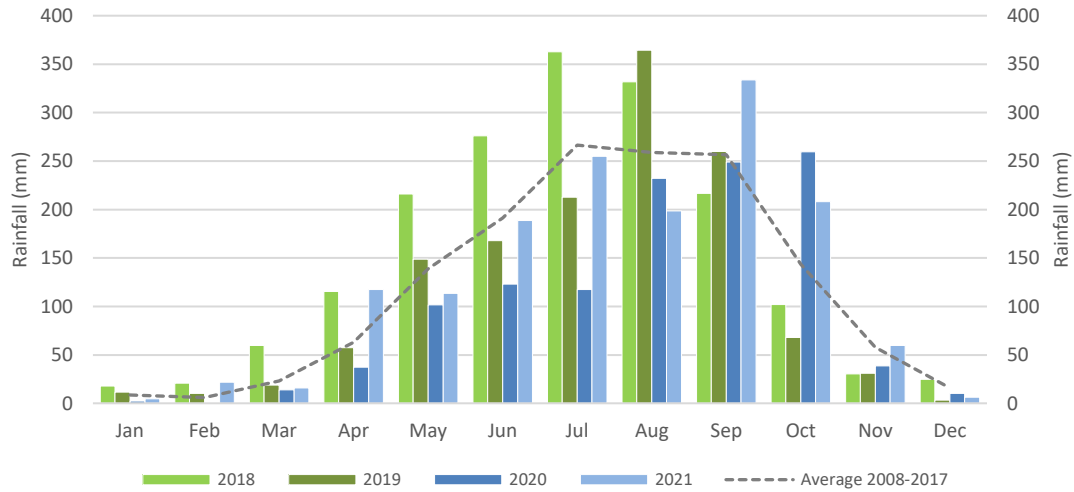


Figure 16. Pattern of monthly rainfall and its anomaly of the Lower Mekong Basin for 2018-2021.

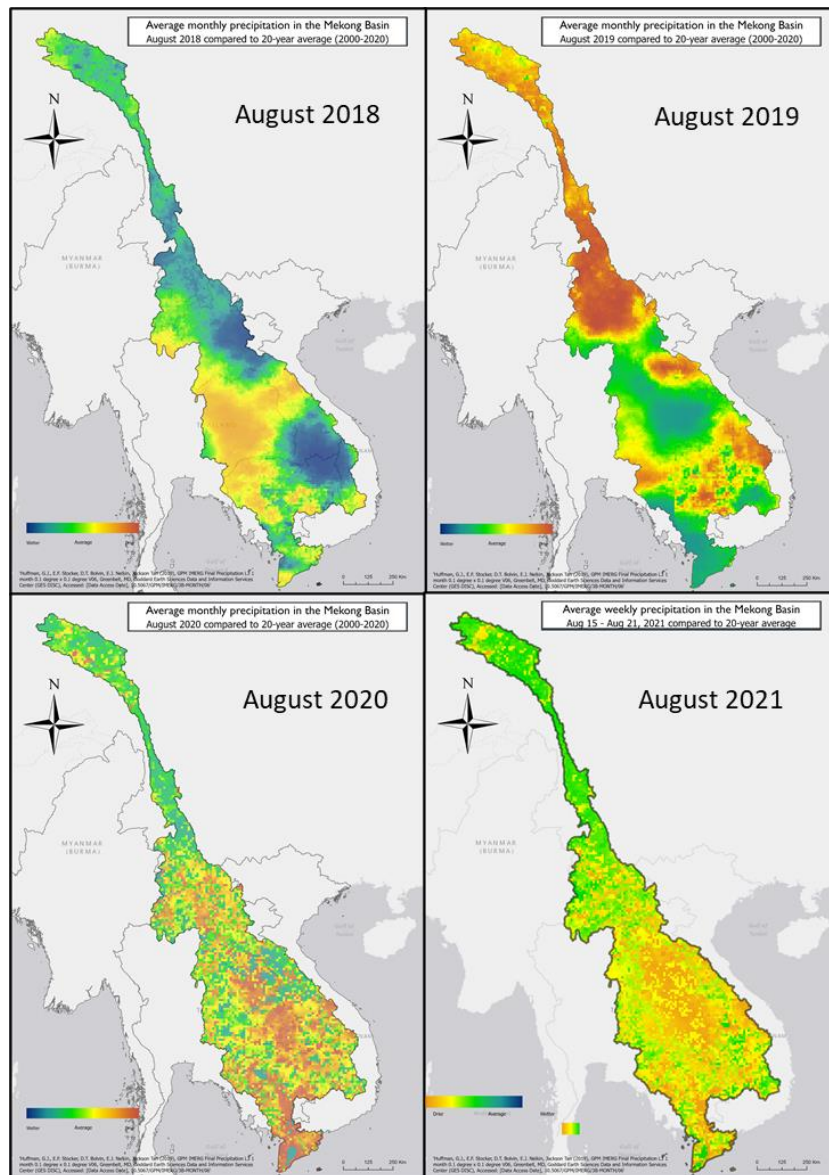


Figure 17. Rainfall anomaly maps for the Mekong Basin for August 2018, 2019, 2020, 2021 (MDM, 2021).

Again, without the benefit of detailed rainfall-runoff and flow routing modelling, it is difficult to draw firm conclusions on the impacts of rainfall on mainstream flows. However, the following deductions can be made from the evidence provided in Annex B and Annex C, Figure 17 and Figure 16:

- Rainfall in 2018 was higher than average for January through to August over large parts of the whole Mekong Basin. Total rainfall over the LMB dipped below average only in the latter part of the wet season, from September to December.
- In the 2019 wet season, rainfall in the UMB was below normal to normal, with August being exceptionally dry and June being somewhat drier than normal.
- In June and July 2019, rainfall was below normal in the LMB. The very low flows in the mainstream over the 2019 wet season are, therefore, likely due to a combination of the reduced flows from the UMB and the lower-than-normal rainfall over the LMB.
- The higher-than-normal rains in August 2019 explain the short peaks in flow at Nong Khai and the downstream stations in September 2019.
- The driest year for the LMB out of the four years investigated was 2020. In 2020 every month, except for October, was below normal. The rainfall anomaly maps for 2020 show that the lower-than-normal rainfall was widespread over the LMB.
- In 2021, the rainfall patterns over the LMB still showed delayed monsoons.
- This, together with the low storage levels at the start of 2020, explains the much lower than normal wet season flows throughout the LMB.
- The rainfall patterns from 2019 to 2021 also explain the reverse flow patterns and total volumes of the Tonle Sap Lake and the increased duration of the reverse flows.

5.5 Climate change and *El Nino/La Nina*

Keovilignavong and colleagues (2021) reviewed various studies pertaining to the causes of drought in the Mekong Basin. They identified four main causes for the drought in the Mekong: climate change, low rainfall, dry weather or high temperature and the *El Nino* phenomenon. They note that few papers studied the relationship between *El Nino* events and the Mekong drought in detail. However, one study by Cosslett and Cosslett (2018) observed that *El Nino* events in 2010 and 2015 caused below average rainfall and a shorter duration of the flood season. Sam and colleagues (2019) also noted a strong relationship between *El Nino* events and drought in the Mekong Basin, especially over the Central Highlands of Viet Nam.

Some international media reported that the late arrival of the monsoon rains, the *El Nino* event, and climate change were important drivers of the drought and low flows in the Mekong (Lovgren, 2019), noting that the primary reason for the 2019 drought was an *El Nino* event. The MRC, in its hydrological condition report of January – July 2020, also cites the *El Nino* event as one of the reasons for the abnormally low rainfall in the LMB. In its Annual Hydrology, Flood and Drought Report, the MRC cites the analyses by the Japanese Meteorological Agency, which reported that the *El Nino-La Nina* phenomena had influenced the drought pattern in parts of Cambodia.

The anomalies of the land/sea surface temperature²⁰ benchmarked the changes in the Mekong against global changes. Quarterly average temperatures for 2018-2021 were compared to the average of the base period of 2008-2017 and presented in Annex F.

The higher temperature in 2019-2020 was noted on the global scale. More specifically, the temperature anomaly for the Mekong region suggests that 2019-2020 were hot dry years. The year 2018 tends to be a normal year; however, the last quarter of 2018 tends to be hotter than usual. Both temperature and rainfall for the Year 2021 vary between the average of 2008-2017.

Several studies reviewed by Keovilignavong and colleagues (2021) suggested that the rainfall deficits and temperature increase due to climate change have driven changes in Mekong's hydrology. Low accumulated rainfall, changing rainfall patterns, and early ending of rainfall seasons have also been reported as causing drought over the Mekong Basin by other authors (Bastakoti et al. 2014). Hung (2017) observed that for an average 1.5°C increase in temperature, average annual rainfall would decrease by 10-15%. Sam and colleagues (2019) found a strong correlation between *El Nino* events and drought in the Mekong Basin, especially in parts of Viet Nam. Leang (2020), Haegen (2020) and Southerland (2019) argue that both climate factors and storage caused the 2019-2020 drought in the reservoirs. According to Leang (2020), warmer than usual temperatures, very low rainfall and reduction in flows from the UMB all lie behind the lower flows in 2019.

Yun and colleagues (2020) studied the impacts of climate change and reservoir operations on streamflow and flood characteristics in the Lancang-Mekong River Basin. They observed that during 2008-2016, the reservoirs in the UMB reduced the annual average streamflow at Chiang Saen but that the impacts on flows downstream of Vientiane were limited. They note that climate change and tributary storage seemed to cause streamflow changes downstream of the Mukdahan station. They also note that climate change increased the magnitude and frequency of floods by up to 14% and 45%, respectively, during 2008-2016 compared to the baseline period of 1985-2007.

NOAA's Climate Prediction Centre has issued an advisory noting a 95% chance of a *La Nina* event over the northern hemisphere winter.

²⁰ The land surface temperature is based on GISS analysis based on GHCN v4 while the sea surface temperature uses NOAA/NCEI's Extended Reconstructed Sea Surface Temperature (ERSST) v5 (NASA, 2022).

Anomalies is the mean temperature averaged over a specified mean of the base period of 2008-2017 with a smoothing radius of 250 km (NASA, 2022).

6 Discussion

6.1 Previous studies

The extremely low flows in the Mekong River and Tonle Sap Lake/River since 2019 have received considerable attention over the last few years, and several studies have aimed to identify the main causes of drivers of the low flows. This section is not a review or thorough analysis of these studies but provides an *outline* of the methodologies used and their main findings.

6.1.1 *The Eyes on Earth (EoE) analysis*

The EoE approaches are based on satellite data to determine reservoir volumes, precipitation as well as the Surface Wetness Index to determine flows. These data were used in a rainfall-runoff model, which was calibrated against the MRC flow gauge at Chiang Saen for the pre-impoundment condition. This is then used to model the 'natural' flow, which is compared to the actual flows at Chiang Saen, with the assumption that the deficit in flows was due to the storage in the UMB. The methodologies used are detailed on MDM (2021). The MDM website acknowledges and discusses the potential errors in the input data.

Eyler and Weatherby (2020), Johnson (2020) and Rujivanarom (2019) argue, based on the EoE study, that the storage in the UMB and Mekong mainstream and on the tributary rivers are a major cause of the low flows in 2019. In an Op-Ed in the Bangkok Post (Eyler, 2020) by Eyler, Basist, Weatherby, and Williams notes:

“The EoE study found that China's upstream dam regulation had severely altered the natural flow of the river and pointed to a massive restriction of water during the 2019 wet season at a time when downstream countries were experiencing weather-driven drought. Under natural flow conditions, a Mekong flood pulse would have been observed at Chiang Saen, however, restrictions from upstream dams neutered that pulse. The study concluded that China's operations of 11 upstream dams exacerbated drought conditions in the lower Basin by restricting the natural flow from China during the wet season.”

The EoE based assessments cite, among other evidence, the sudden decreases in flows at Chiang Saen in July 2019 as the key evidence for their conclusions (see Figure 7). These papers also point to larger storage in the LMB as an underlying cause of the flow disruptions.

The findings from this study received immediate reaction from the Mekong research community: Tarek et al. (2020), and Kallio and Fallon (2020).

6.1.2 *The Tsinghua University analysis*

The Tsinghua University in collaboration with the China Institute of Water Resources and Hydropower Research (Tian, 2020) used slightly different approaches and input rainfall data to the EoE assessments. The Standardised Precipitation Evapotranspiration Index and the Standardised Precipitation Index were used to assess the intensity and extent of drought in the Lancang-Mekong River Basin (LMRB). River flows were based on the THREW distributed hydrological model for the whole Basin. The rainfall input data came from both surface rainfall measurements across the whole Basin, and the same MRC flow gauges were used as reported above.

The impacts of the storage in the UMB were also based on determining ‘natural’ pre-storage flows and comparing them to post storage flows. These methods are detailed in the China Institute of Water Resources and Hydropower Research (2020).

Unsurprisingly, the results of the two studies are very similar. However, the Tsinghua University study places more emphasis on drought as the main driver of the low flows. They note that “*severe and exceptional droughts occurred more frequently during the recent 59 years compared to its previous 60 years, and the recent 59-year results show that drought hot spots locate principally in the middle and upper parts of the Lancang sub-region.*” They suggest that the 2019 drought was one of these, arguing that the whole Basin experienced severe drought conditions from April 2019 to at least August 2019. They also note that the storage could be used to alleviate the impacts of drought.

The basis of this emphasis is that, while the UMB contributes significantly to the annual discharge at Chiang Saen making up 64.4% of the flow at this site. This proportion decreases downstream, making up 39.5% of the flow at Nong Khai, and 14.3% at Stung Treng. These figures were not disaggregated into the wet and dry seasons, nor for 2019.

6.1.3 The MRC analysis

In response to the considerable brouhaha caused by these studies in the press, the MRC Secretariat produced a Technical Note on the low flow conditions in April 2020. That note was based on cumulative rainfall over the LMB compared to historical records, Standardised Precipitation Index maps, temperature anomaly maps and the PMFM flow data. No hydrological modelling was undertaken, and the conclusions were drawn from a heuristic assessment²¹ based on an understanding of the flow conditions in the Basin.

The MRC concluded that the LMB was in the grip of a severe two-year (at that time) drought with lower-than-normal rainfall over much of the LMB. The report noted that the total reverse flow volumes into the Tonle Sap were considerably lower than in 2018, and that this would have a severe impact on the economies of Cambodia and Viet Nam. The report did not analyse the impacts of the changes in storage, apart from noting that the drought was a major factor driving the low flows noted.

The report concluded that the MRC must explore operational management options for drought and flood mitigation, as well as the potential for additional jointly operated storage. These recommendations reflect the studies outlined in the Basin Development Strategy 2021-2030 and the MRC Strategic Plan 2021-2025.

6.2 This report’s heuristic analysis

None of the above assessments is fundamentally wrong. They use the slightly different approaches and datasets and come up with subtly different results on the impacts of storage on flow. They, however, draw widely different conclusions on the relative contributions of the different sources. The EoE studies point the finger at the low flow conditions, mainly at the storage in the UMB. The Tsinghua University study suggests the unusually severe drought conditions in the Mekong Basin and indicates that the storage could mitigate the low flows. The MRC assessment does not point to either cause as the primary

²¹ A heuristic, or heuristic technique, is any approach to problem-solving that uses a practical method or various shortcuts in order to produce solutions that may not be optimal but are sufficient given a limited timeframe or deadline (Chen, 2021).

driver of the low flows. It does, however, note the severe drought conditions in the LMB and that this would have affected flows in the river.

The current study does not attempt to model the 'natural' and post-storage flow conditions, and like the previous MRC's analysis is based on a heuristic analysis of the data. It recognises the only way to draw firm conclusions as to which of the two drivers were most responsible for the low flows would be to develop a comprehensive water balance model of the whole Basin, based on actual inflows and outflows of each of the reservoirs, as well as a calibration based on all the flow gauges in the mainstream. We, however, feel confident in drawing the following general conclusions based on similar datasets but incorporating an assessment of the changes in storage. The report also focuses on the reverse flow to the Tonle Sap Lake as a bellwether of the overall flow conditions in the Mekong Basin.

The following analysis is based on the collective of all the available data listed above.

In 2019:

- The UMB was drier than normal in the 2019 wet season. August specifically was very dry over much of the UMB.
- This is evident in the storage in the two major reservoirs, which stored less water in the 2019 wet season ($\approx 10 \text{ km}^3$) than in typical years to 2021 wet seasons ($\approx 20 \text{ km}^3$).
- The lower net storage in the UMB in the wet season of 2019 must have been due to lower-than-normal inflows.
- Some releases were made through the turbines to generate power. But it is likely that the operators were very cautious about making additional releases in the wet season, to avoid risking power generation in the following dry season.
- Inflows at Chiang Saen in the 2019 wet season were therefore 46% of the average.
- In somewhat of a perfect storm, much of the LMB was also suffering from low rainfall. Thus, there were also lower than normal inflows from the tributaries. Thus, flows at Stung Treng were 71% of the average.
- There were, nonetheless, some wet months (August and September) in the lower reaches of the LMB. This contributed to shorter duration high flow events seen downstream of Nong Khai.
- The Tonle Sap Lake had slightly less than the average total reverse flows, which were helped along by the short periods of higher flows.
- The duration of the reverse flow in 2019 was the lowest since 2008. Lake levels only started to increase noticeably in August as opposed to June.
- The Tonle Sap catchment also suffered a particularly dry, wet season and hence the contribution from the local catchment was also reduced.
- The combination of these events appears to have impacted on total fish abundance and biomass in the Lake and affected farmers and freshwater supplies in the Delta in the first few months of 2020.
- The 'deficit' in wet season flows at Chiang Saen (-28.50 km^3) is about one third of the 'deficit' in flows further downstream (-90.80 km^3 at Stung Treng). This suggests that, while the storage in the UMB played a role in the lower flows, its influence was smaller than the impacts of the drought in the LMB.

In 2020 and 2021:

- In 2020, the total storage in the Mekong Basin at the start of the dry season was approximately 50% lower than normal. This carried over into the 2020 wet season.

- In 2020, rainfall over the UMB trended normal to above-normal, and after July, the storage patterns returned to close to the full supply levels by October. This pattern was repeated into 2021.
- In the LMB, the rainfall trends were below normal for both years and characterised by extremely dry periods over parts of the Basin. The monsoon rains were delayed, and the total annual rainfall was lower.
- The deficit in total accumulated wet season flows at Chiang Saen was lower in 2019 and the dry season deficit of -5.62 km^3 did not continue into 2021.
- Further downstream the impacts of the reduced rainfall in the LMB resulted in increasing wet season flow deficits further downstream. As in 2019, flows were characterised by shorter periods of higher flows.
- Reverse flow volumes into the Tonle Sap Lake were the lowest and second lowest on record. The period of the reverse flows was, however, longer than normal due to the delayed monsoons.
- Rainfall in Cambodia was below normal for much of the period, most likely also contributing to lower local catchment contributions to the Lake.

Overall observations:

- The total storage in the UMB's two largest reservoirs in 2019 was about half of that in 2018 due to the very dry conditions over the UMB.
- Apart from 2019, the patterns and volumes of water stored in the UMB have been similar since 2015. However, the extremely low flows in the LMB due to the lower-than-normal precipitation over the UMB have only been evident in 2019, 2020 and 2021, with the last two years being the most critical.
- Rainfall over the LMB in the first half of the wet season (May to August) has been lower since 2019, with particularly low rainfall in 2020. However, the latter part of the wet season (September and October) saw higher than normal and patchy rainfall, reflecting the delayed monsoons.
- This has resulted in a later start and longer duration to the reverse flows, with the overall reverse flow volume for 2020 and 2021 being the lowest on record, despite the fact that more water was stored in the UMB than in 2019.

Therefore, the lower rainfall over the LMB appears to be a stronger driver of the extremely low flows in the Mekong mainstream, at least below Nong Khai.

6.3 Reasonable and equitable use

The issue of large storage in the UMB and LMB affect the natural flow patterns is undeniable since the reservoirs are built to provide more assured generation capacity in the dry season by storing water in the wet season. Clearly, the Xiaowan and Nuozhadu Reservoirs stored some water in the 2019 wet season, despite the much lower inflows. But this was less than in most years. This reduced the wet season inflows into the LMB, as is evident from the records at Chiang Saen. However, the need to generate power also meant that some flow was allowed through. The overall impact of storage, resulting in higher dry season flows and delayed and lower wet season flows, is also evident from this study.

A more pertinent issue would be *“whether China acted reasonably and equitably in the 2019 wet season, given the severe drought in the LMB, and whether the hydropower in the UMB and LMB is a*

reasonable use of the Mekong River System". This is a much more nuanced question to resolve. Even though China is not a party to either the 1995 Mekong Agreement or the 1997 UN Convention on the Non-navigational use of Shared Watercourses, it will enjoy the same customary international rights as the downstream riparian countries. This includes reasonable and equitable use, as well as the avoidance of significant harm principles.

7 Drought Management Options

The construction of storage has been the go-to solution to drought management for many years. More recently, drought prone basins are reaching the limits of constructing new storage and have shifted towards water allocation and water demand management to accommodate deficits between water availability and water demands (Quibell et al., 2013). Speed and colleagues (2013) provide a treatise on Basin Water Allocation Planning in this context. Both these options could be explored in the Mekong Basin context. Indeed, water allocation planning lies at the heart of the original intention of Articles 5 and 6 of the 1995 Mekong Agreement. This section briefly explores these options in the Mekong Basin context.

7.1 Building more storage

The objective of building storage is to store water when the availability exceeds demands (surplus water as per Article 26 of the 1995 Mekong Agreement), and to release it when demand exceeds availability. The long-term water yield of a basin is consequently a product of both the runoff and storage (Figure 18). However, there are two codicils to this, firstly as more storage is built, there is less surplus water and the storage to yield curve flattens out (Figure 19). This is also affected by the availability of suitable dam sites. The unit cost of the water stored therefore increases as more storage is built. Secondly, the more surplus water stored the greater the impact on the natural flow regimes and hence the greater the ecological impact²².

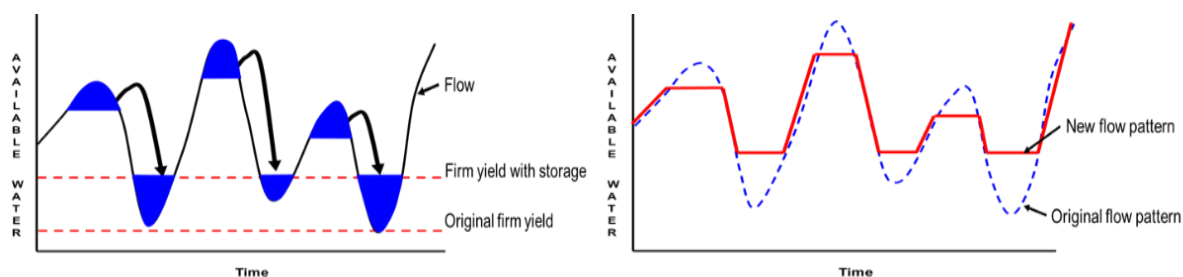


Figure 18. A conceptual diagram of the impacts of building storage to capture surplus water.

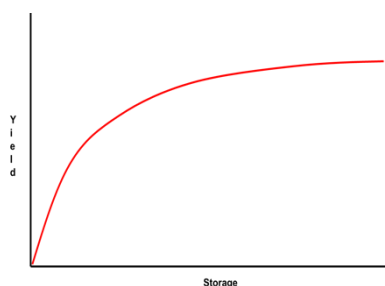


Figure 19. A conceptual diagram of the yield to storage curve.

²² The ecological impacts result from river discontinuities (blocked migration), lost flowing water habitat under the reservoir, changed water quality, and from disrupted natural flow regimes.

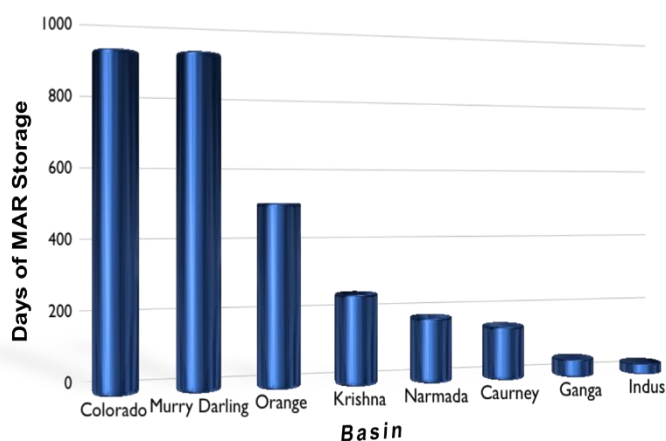


Figure 20. The days of MAR that can be stored in major basins in the world. (Quibell et al., 2013).

The impact of storage on the ability to manage flows depends on the number of days of the Mean Annual Runoff (MAR) that can be stored. Figure 20 presents the days of MAR that is stored in several major drought prone basins in the world. The Colorado and the Murray Darling Basins can store over 2 years of the MAR, in the Orange-Senqu about 18 months of MAR can be stored. Drought management in these basins takes place over several years. In the Mekong Basin, active storage is approximately 46.796 km³ (Table 2). This is about 10% or 33 to 34 days of MAR. The use of the existing

storage in the basin would therefore be restricted to short term interventions on a seasonal or even sub-seasonal basis.

The 1975 Joint Declaration between the LMB Member Countries outlined proposals for building joint storage for hydropower, as well as flood and drought management. However, the rapid development of hydropower on a sovereign basis means the opportunities for building joint storage for flood and drought management now dwindles. Building sufficient storage to allow for more active interventions to manage flows will also be restricted by the availability of suitable dam sites and the increasing ecological impacts.

7.2 Managing water allocations

Changing the allocations of water in drought periods was implicit in the analysis undertaken by the Tsinghua University. In principle, their suggestions require allocating less water to assure hydropower production in the wet season in favour of environmental flows. If this is to be adopted, the risks of reduced energy outputs and electricity shortages would have to be shown to be negligible. The risks to reduced energy outputs for the remainder of the wet season and into the following dry season would have to be determined using stochastic analyses based on historical flow and energy use patterns or would require a Monte Carlo²³ simulation of the likely rainfall patterns based on seasonal forecasts. Consideration could also be given to conjunctively reducing water abstractions for irrigation purposes.

Given the availability of storage throughout the Basin, this would only be viable if the storage in the UMB is included in the analysis and management proposals. In this regard, Wouters and Chen (2018) quote President Xi of China as follows:

“... we should boost cooperation as an effective vehicle for enhancing common development ... While pursuing its own interests, a country should accommodate the legitimate concerns of others... We need to work vigorously to create more cooperation opportunities, upgrade

²³ A Monte Carlo simulation is a technique that allows managers to account for the risks in quantitative analysis and decision making (Palisade, 2021).

cooperation, and deliver more development dividends to our people and contribute more to global growth.”

However, they go on to highlight that China’s approach to transboundary water cooperation is constrained by its territorial sovereignty approach. China did initially share wet season data from the Jinghong site, to support potential flood management. Recently, they have started sharing year-round data. At the 25th Dialogue Partner Meeting in 2021, China also suggested that a joint notification mechanism should be established as soon as possible. This should inform all the Mekong countries of emerging flood and drought conditions, to facilitate emergency responses.

The Lancang-Mekong Cooperation mechanism was established in 2016, with China at the helm. There may therefore be opportunities to build on the theme of ‘China as a good neighbour’ through this mechanism, and by making *requests* for compensation releases based on balancing the risks of reduced energy outputs, with the benefits to the LMB and reverse flows into the Tonle Sap Lake.

7.3 Other adaptation strategies

A range of other adaptation strategies across the Water-Food-Energy nexus could also be considered, including:

- Building more renewable, non-hydropower, sources of energy.
- Managing energy demands, particularly in the peak summer months.
- Shifting to more drought resistant crops and crop diversification.
- Shifting economies gradually towards more water and energy efficient growth, while ensuring that the basic food needs of the poor are protected.
- Rainfall augmentation or artificial rainmaking technique.
- Small scale pond or ‘Monkey Cheek’ reservoir project.

8 Conclusions

The flow patterns in the LMB are driven by a variety of factors, underpinned by the rainfall-runoff characteristics and how much of that runoff is stored in the wet season and released in the dry season. Increasing dry season flows and lower wet season flows are characteristic of the expansion of storage in the Basin. This storage has a range of adverse effects on ecological functioning, beyond just the changes in flow regimes. But for the purposes of this report, the following conclusions can be drawn.

- While the reservoirs in the UMB stores water in the wet season, this was less marked in 2019. The upshot of this was that flows from the UMB were lower in the dry season of 2020. This was due to the drought conditions over the UMB.
- From 2019 to 2020, wet season rainfall over the LMB has been lower in June and July and the total cumulative rainfall has been lower-than-normal.
- Rainfall patterns have shifted with higher rainfall occurring later, in September and October of 2020 and 2021.
- This has delayed the start of the reverse flows into the Tonle Sap Lake, decreased the total volume of the reverse flow, and extended the period of the reverse flows.
- This appears to have decreased the abundance and biomass of fish in the Tonle Sap and created considerable hardship and economic losses for the people of the Delta in the following dry season.
- While the two largest reservoirs in the UMB were commissioned in 2010 (Xiaowan) and 2014 (Nuozhadu), flows in the LMB have only reached extreme low levels from 2019 to 2021. This points to the lower rainfall over the LMB as being the primary driver of the low flows in these years (only 2018 was a wet year). Further weight to this comes from the observation that the 'deficit' in flows increases downstream, and the reduced flows at Chiang Saen are 31% of those at Stung Treng.
- This pattern of rainfall of the LMB is likely to be associated with the *El Nino* event as well as climate change.
- The opportunities for active management of the flows in the LMB, as originally envisaged in Article 6, are limited. But it may be possible to adjust the flows in the mainstream and consequently the reverse flows in the Tonle Sap Lake using the existing storage. These actions must include the storage in the UMB to make any meaningful difference.
- Any model to support these operations must balance the risks to hydropower generation with the benefits to the timing and volume of the reverse flows into the Tonle Sap Lake.
- The risks to energy production will decrease with the duration of the wet season, as greater certainty emerges over the likely levels of storage at the end of the wet season. This means that requests to the operators of the reservoirs to release more water are more likely to find fertile ground towards the end of the wet season. However, seasonal forecasts of rainfall may provide more certainty earlier in the wet season.
- Other drought management options should also be considered.

9 Recommendations

The following recommendations are made:

1. A more conclusive answer to the question of the proportion of the flow that is held back in the storage reservoirs versus the reduced inflows due to 'drought' or increased inflows due to 'flood' is most reliably based on water balance modelling in each reservoir, which requires data that is not yet available to the MRC or previous studies.
2. A 'operational model' of the whole Mekong River Basin needs to be built. This model should include the management and storage operations:
 - a. be updated in near real-time using the information on the active storage across the whole Basin.
 - b. present and analyse options to determine the impacts of releases on the timing and volume of the reverse flow for the remainder of the wet season and forecasts of the seasonal rainfall/runoff across the Basin.
 - c. outline the risks to energy production based on the options tested in point (b).
 - d. be based on the water releasing infrastructure at each large reservoir that is included in the model, i.e., could it be physically possible to make compensation releases?
3. Options to build more storage, operated primarily for water security enhancement, should be explored per the direction of the Basin Development Strategy 2021-2030. This should address:
 - a. the identification of suitable sites and the volumes of water that could be stored.
 - b. the potential adverse effects on resettlement, sediment transport and aquatic ecosystems.
 - c. the institutional arrangements required for a project coordination authority.
4. Given the consequences of extremely low flows and as per the proposal at the 25th MRC Dialogue Partner Meeting with China and Myanmar in 2021 on future cooperation, an enhanced or joint notification mechanism should be established as soon as possible. This should inform all the Mekong countries of emerging flood and drought conditions, to facilitate emergency response.
5. The Basin Development Strategy 2021-2030 clearly draws out the importance of enhanced information sharing and coordinated operation management of reservoirs and hydropower dams, particularly for transboundary flow management, and emergency situations. Toward this end, there is a strong need for more proactive cooperation approaches, bolder leadership and collective action from all the MRC Member Countries as well as China across the entire Lancang-Mekong River Basin.

The above recommendations will be further explored, discussed and worked with the MRC Member Countries, China and the LMC Water Center, in ongoing work such as the Joint Study on the Changing Hydrological Conditions and Adaptation Strategies as well as the Proactive Regional Planning.

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Annex A: Do low flows influence the fish catch in the Tonle Sap River and Lake?

The Tonle Sap River and Lake (TSRL) forms the largest natural wetlands in the Mekong Basin and southeast Asia due to its vital portion of the Mekong's hydrological system and a unique tropical flood pulse with a flow-reversal system (MRC, 2005; Adamson et al., 2009). There were two Ramsar sites at TSRL: Boeng Chhmar designated in 1999, and Prek Toal in 2015 (The Ramsar Convention Secretariat, 2014). The TSRL is home to birds, reptiles, plants and mammals (Campbell et al., 2006) and also one of the world's largest inland fisheries and richest fish species (Baran et al., 2013). The annual estimated production of Cambodia inland capture fisheries was 767,000 tonnes, of which about 70% was contributed by TSRL (Fisheries Administration, 2013; Hortle & Bamrungrach, 2015).

In recent years (2019 - 2021), it was observed that the reverse flow into Tonle Sap Lake (TSL) decreased to below the long-term average due to significant low water inflows from upstream caused by low average rainfalls (MRC hydrological database, 2021). Lu and Chua (2021) also found the same, yet they concluded that infrastructure projects (e.g. hydropower dams upstream) contribute to the low water inflows as well. It was previously reported that fish catch of TSRL had a positive relationship with water level. Whether or not the low flows of TSRL causes the fish catch at TSRL to drop. Hence, this study aims to (i) describe the temporal variation of fish catch (or relative fish abundance and biomass) and (ii) explore the relationship between fish catch and water level at TSRL.

The study used time-series fisheries monitoring data which were collected by using a fisheries-dependent monitoring programme implemented by Tonle Sap Authority and Inland Fisheries Research and Development Institute (IFReDI) in Cambodia with financial support from the MRC. The daily fish catch data at six monitoring sites (five sites at the Tonle Sap Lake and one at Tonle Sap River) from 2012 to around mid of 2021 were explored. Each site consists of three fishers who collected and recorded their daily fish catches, including individual fish weight, total fish weight, number of fish, and fishing effort. Note that the fish catch data of the five sites at the TSL were averaged to represent the TSL. The local polynomial regression smoother and linear regression were used to assess the long-term temporal variation of the fish catch and water level and the relationship between the fish catch and water level, respectively.

No significant change in fish catch was observed from 2012 to 2015 at TSL (Figure A-1[a][c]), yet the downward trend was quite obvious from 2019 to around mid-2021. The significant drop of fish catch has a strong correlation with water level ($P < 0.05$) (Figure 3ac) as the water level decreased sharply from the same period (Figure A-2[a]). Unlike TSL, the fish catch of TSR showed a small range of variation between 2012 and around mid-2021 (Figure A-1[b][d]), although the water level at TSR steadily dropped (Figure A-2[b]). This reflects the finding of the linear regression model showing no correlation between fish catch and water level ($P > 0.05$) (Figure A-3[b][d]). This might be due to a bias in data collection since the national team leader from IFReDI stated that the participating fishers usually went to catch lots of fish accumulating outside fish cages for foraging additional feed left over from the farmed fish grown in the cages installed along the TSR.

In short, the temporal trend of fish catch at TSLR varied between the studied period with a declining trend in the recent years, and a significant decline was observed in TSL. It was concluded that the water level had a strong influence on fish catch, reflecting the findings of the previous studies.

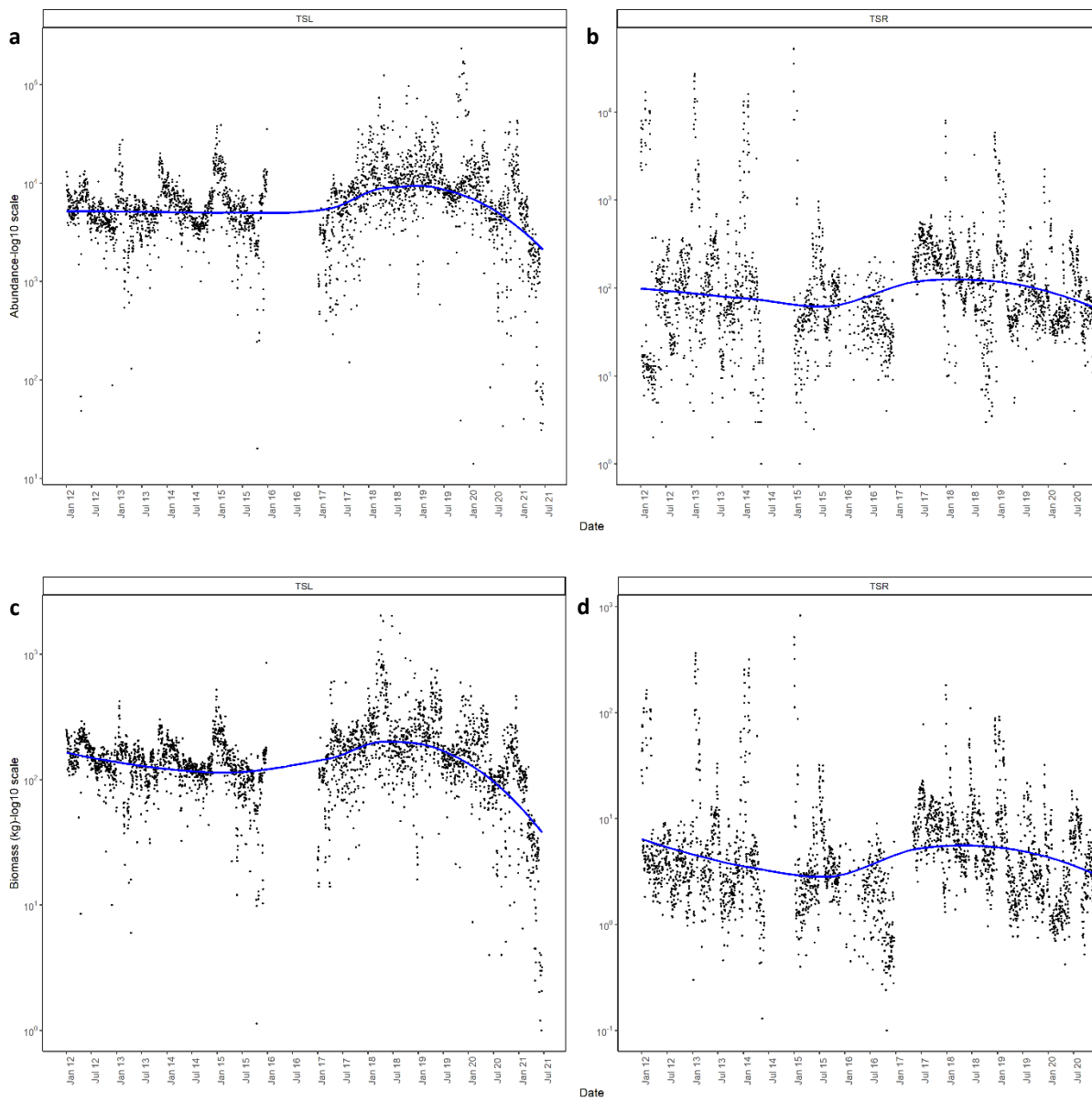


Figure A-1. Monthly variation of fish abundance at (a) Tonle Sap Lake and (b) Tonle Sap River; and fish biomass at (c) Tonle Sap Lake and (d) Tonle Sap River during 2012 – 2021 monitoring period.

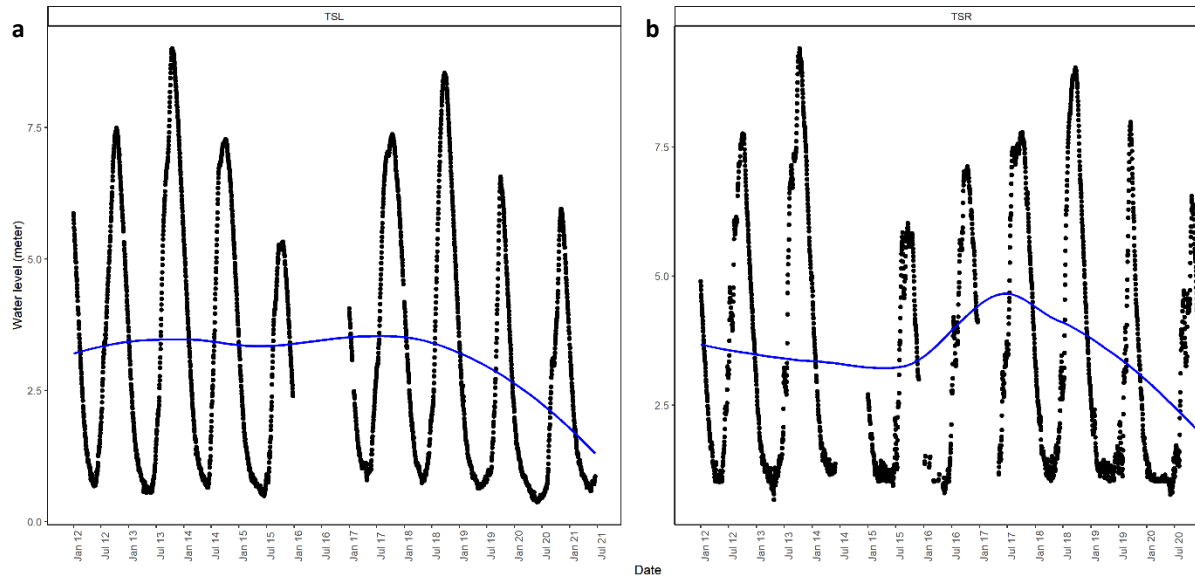


Figure A-2. Monthly variation of water level at (a) Tonle Sap Lake and (b) Tonle Sap River during 2012-2021 period.

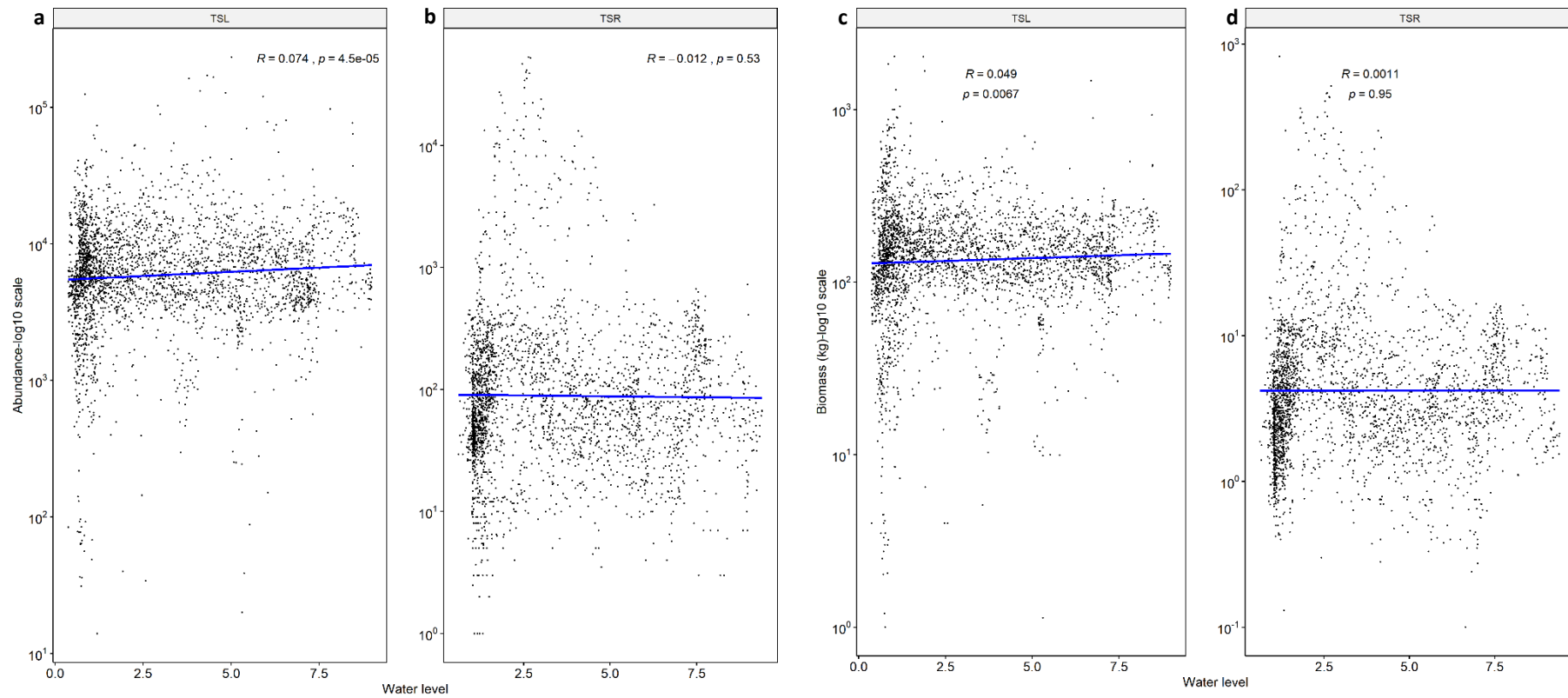


Figure A-3. Relationship between water level and fish abundance at (a) Tonle Sap Lake and (b) Tonle Sap River; and biomass at (c) Tonle Sap Lake and (d) Tonle Sap River.

References of Annex A

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Annex B: Accumulative rainfall for 2018-2021

To inform a clear picture of the low flows and drought in the Mekong since 2018, it is necessary to analyse the regional climatic conditions and river discharge and water levels. Rainfall is the most important variable which reflects the local climatic conditions, and its pattern gives hints about climate disasters such as droughts and floods. The monthly rainfall trends and anomalies in the LMB for the years since 2018 are illustrated in Figure 16. The trends are also compared with that of 2008-2017 average. The rainfall patterns show that LMB received comparatively lower rainfall during the onset of wet season in the years since 2019. Though the year 2019 saw above average rainfall in August and the same as long term average in September, other months experienced shortfall compared to 2018 and 2008-2017 trends. The LMB experienced above average rainfall in 2018 until September and then it decreased to below average levels. This higher rainfall during the dry season and early wet period in 2018 led to similar flows as that of 2008-2017 average (as in Figures 2 and 3). However, the sharp fall in rainfall since September corresponds to sudden drop in discharge in 2018. It is evident that since 2017, the rainfall is unusually low for the months of October and November except for the year 2020, signalling an early withdrawal of monsoon. The year 2020 experienced the driest conditions so far. The dry conditions continue to 2021 as well.

The monthly rainfall anomaly in the years 2018, 2019, 2020 and 2021 are also shown from Figure B-1 to Figure B-4. As explained earlier, the year 2018 saw above average rainfall until August and then it dropped below 2008-2017 rainfall. In general, the years 2019, 2020 and 2021 experienced below average rainfall both in dry and wet seasons, except for August, September and October, respectively.

Overall, the monthly rainfall and anomaly patterns show reduced and erratic rainfall during the recent years, especially in wet season. The anomaly is greater during the onset of wet period, which partly explains the low flow and drought.

The accumulated rainfall for each month in 2018 in the LMB (Figure B-1) shows sparse rainfall in January and the rainfall gradually picking up intensity towards the wetter months. The rainfall rate initially gathers momentum in the central west region of the LMB during April and then moves towards the eastern part from May onwards. Though the high rainfall (more than 400 mm) is confined to some areas such as northeast and southeast LMB in May and June, by July the high intensity rainfall spreads to almost all major stations along the Mekong from Luang Prabang to Stung Treng. By October the rainfall rate is reduced and by November the monsoon withdrawal starts. Overall, in the year 2018, the rainfall distribution was not uniform across the LMB and the eastern part of the LMB received relatively higher rainfall during the wet season.

From Figure B-2, it can be observed that the onset of monsoon rainfall was delayed by about a month in 2019 when compared to the 2018. The monsoon peaked in the month of July in 2018, whereas it peaked during August in the year 2019. By October 2019, the monsoon showed withdrawal signs, especially in the north-central parts of the LMB. As in 2018, the eastern parts of the LMB received relatively higher rainfall during the wet season. The upper stations such as Chiang Saen and Luang Prabang received no or less than 100 mm of rain during most of the time in 2019, which might explain the low flows and water levels in these stations.

The year 2020 saw much worse rainfall conditions as evident from Figure B-3. The peak rainfall of more than 400 mm was mostly confined to certain pockets such as Paksane in western Laos, Nong Khai in north-eastern Thailand. The rainfall was sparse and spatially non-uniform for all the months including the wet months. The central part of the LMB (mostly in Thailand) received below average rainfall for most of the time in 2020. By October, the eastern part of LMB (eastern Laos) received uniform and higher rainfall, however this trend was short lived. Thus, the yearly peak rainfall shifts from July in 2018 to October 2020. This explains the shift in water flow and level peaks to the right in 2020. Except for about four months, most of the LMB areas received no or below 200 mm rainfall. The very dry conditions in the dry season combined with erratic rainfall conditions in the wet season can mostly be blamed for the record drought and low flows in 2020.

In the year 2021, the upper parts of western LMB received rainfall in the range of 200–300 mm in April followed by the same conditions in May (Figure B-4). Peak rainfall was concentrated in areas south of Luang Prabang and north of Mukdahan. The rainfall gathered strength during July, however lost the intensity in August. Though not uniformly distributed, the peak rainfall conditions can be observed in September 2021. The Mekong Delta region in Viet Nam received peak rainfall in October.

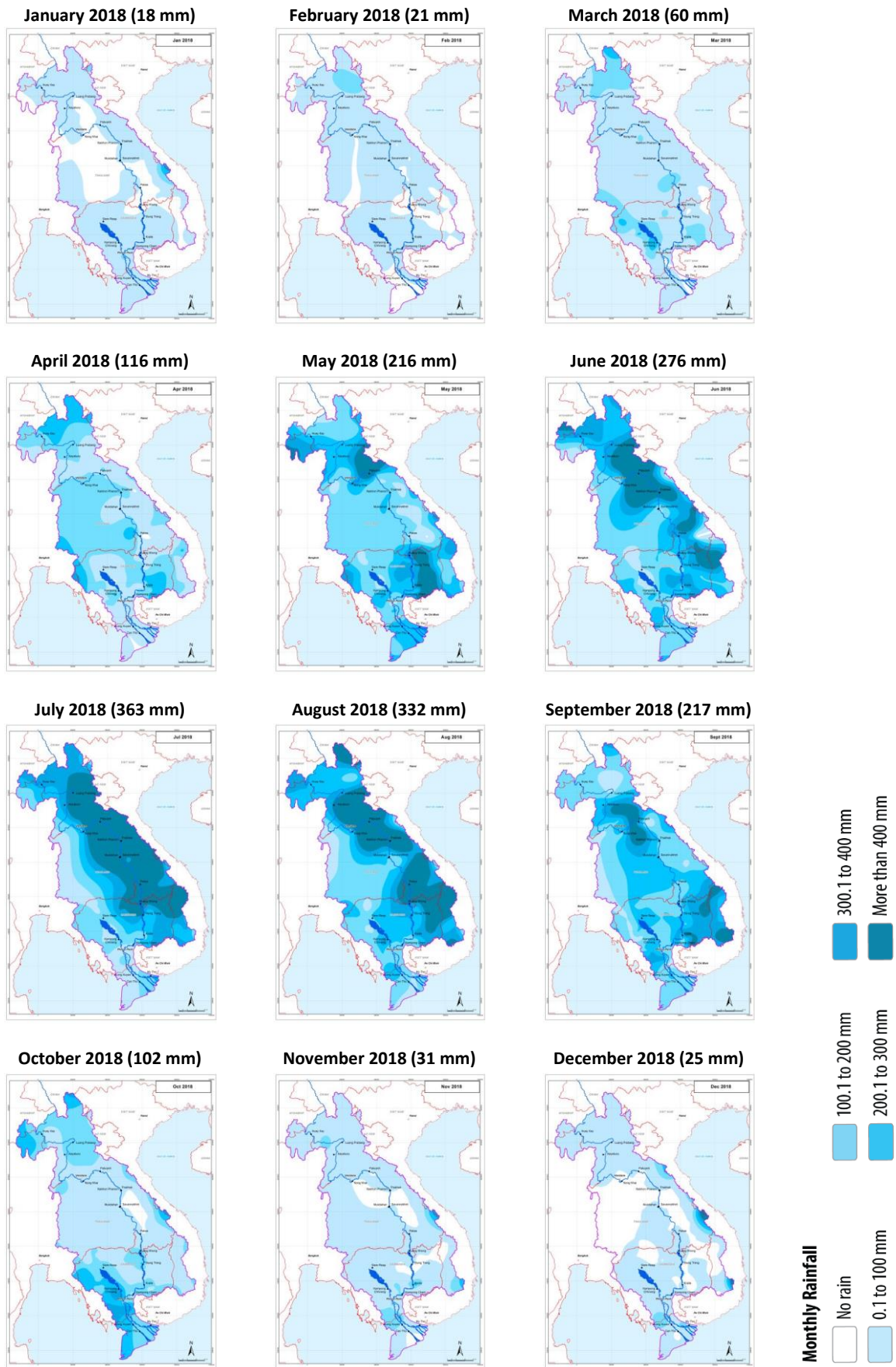


Figure B-1. Accumulated monthly rainfall for 2018, generated from 119 rainfall stations in the Lower Mekong Basin. Amount of rainfall presents in mm.

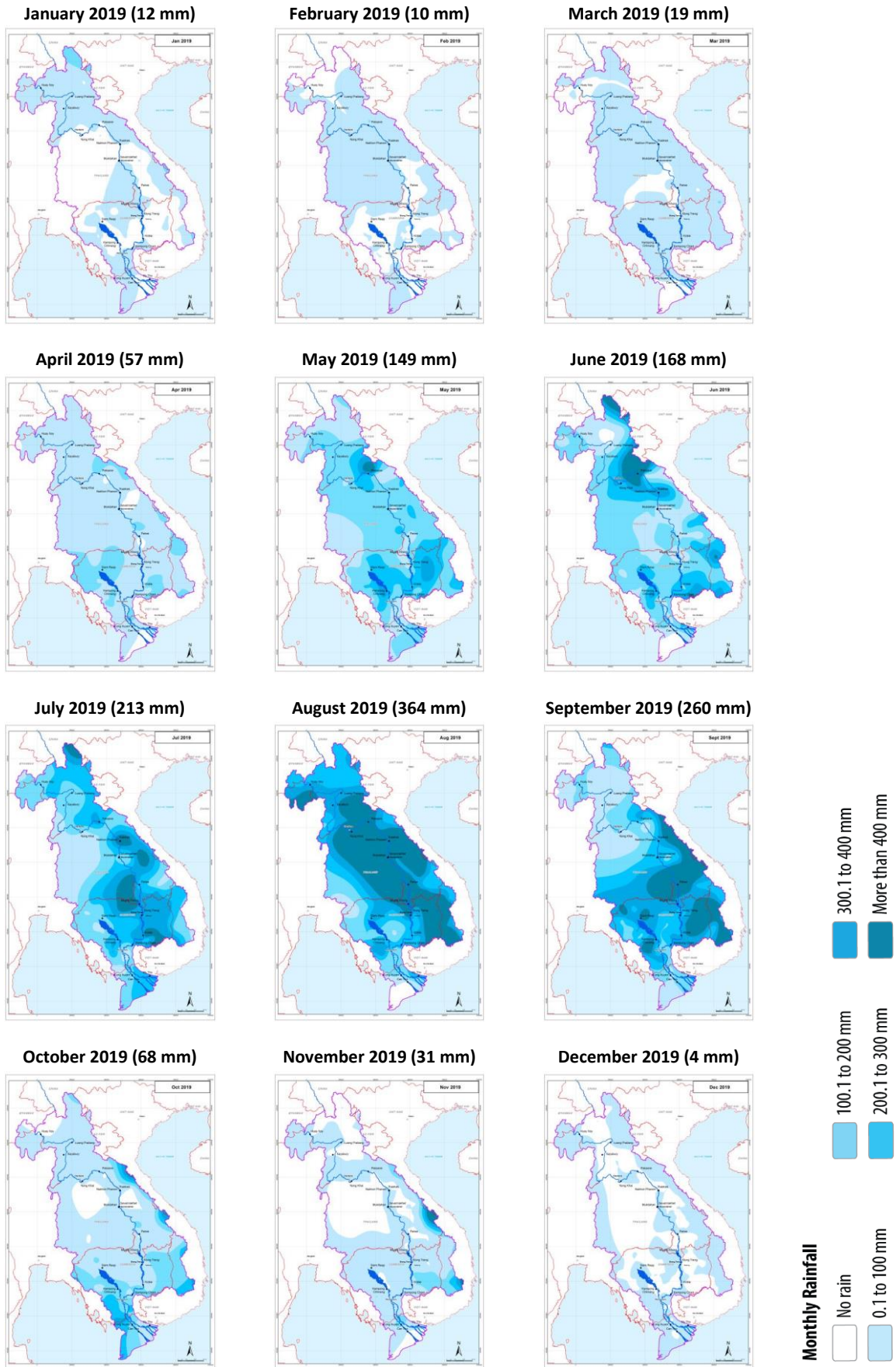


Figure B-2. Accumulated monthly rainfall for 2019, generated from 119 rainfall stations in the Lower Mekong Basin. Amount of rainfall presents in mm.

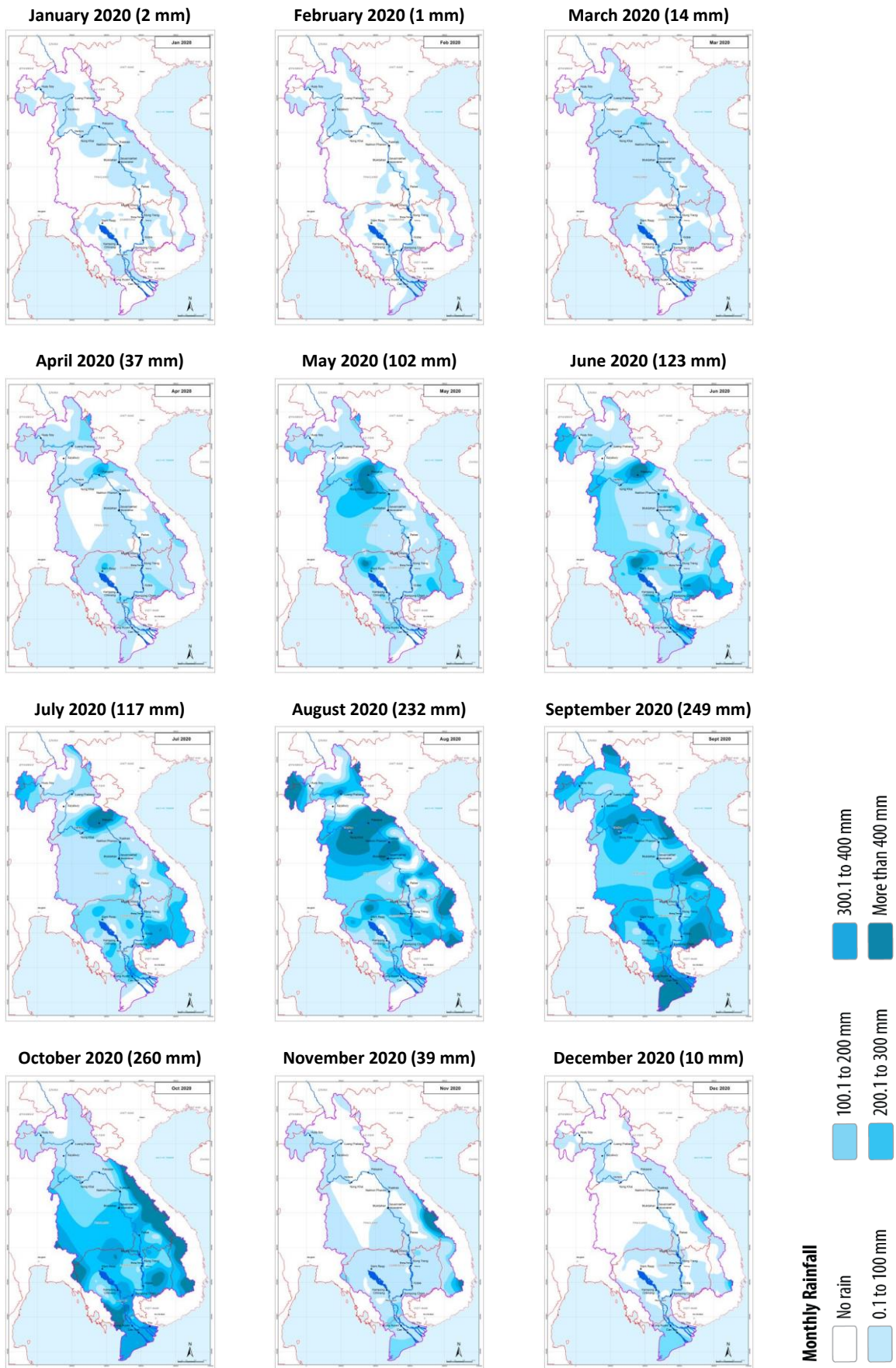


Figure B-3. Accumulated monthly rainfall for 2020, generated from 119 rainfall stations in the Lower Mekong Basin. Amount of rainfall presents in mm.

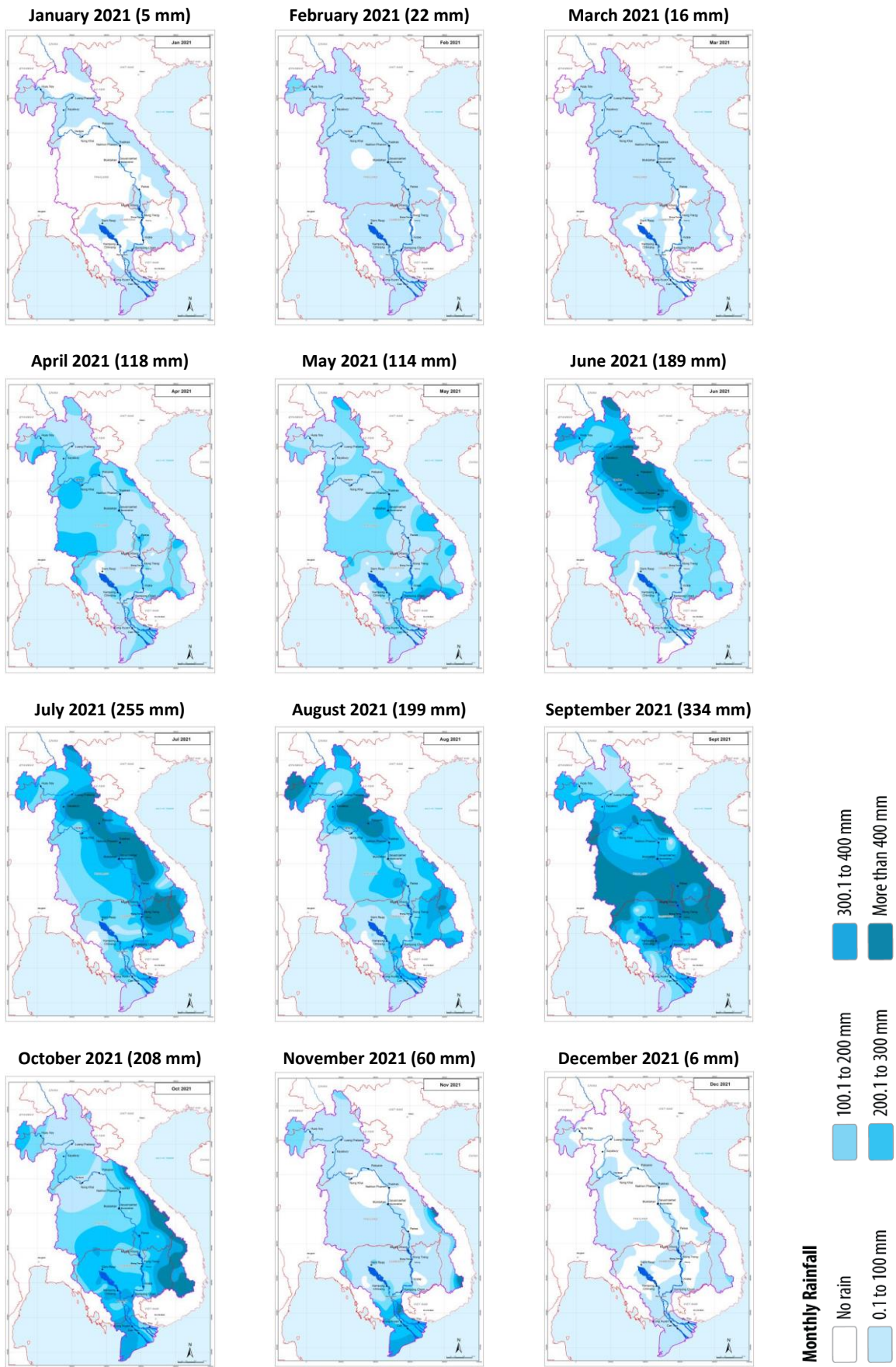


Figure B-4. Accumulated monthly rainfall for 2021, generated from 119 rainfall stations in the Lower Mekong Basin. Amount of rainfall presents in mm.

Annex C: Monthly rainfall anomalies for 2018-2021

The anomaly patterns of monthly rainfall for years 2018, 2019, 2020 and 2021 as compared to 2008-2017 period show that there is a change in the local rainfall patterns since 2018. The changes are mostly felt in the region downstream of Luang Prabang and upstream of Stung Treng. The negative anomaly is prominent during the wet season, when high flows are expected in the Mekong region. This high flow is very much essential for the environmental, economic and social well-being of ecosystem supported by Mekong. Therefore, a comprehensive study investigating the changing local rainfall pattern (global climate change, *El Nino* etc.) would shed some insights into the causes of such anomalies.

The anomaly patterns in 2018 as in Figure C-1 show that the dry season and initial period of wet season until September received higher than average rainfall. From September onwards until December, the rainfall marked reductions from the average, indicating early withdrawal of the monsoon. This might explain the earlier than usual drop of flow and water level in stations downstream of Chiang Saen Figure 7 and Figure 8. It is interesting to note that for most of the months, areas upstream of Xayaburi received more rainfall compared to the average 2008-2017 rainfall. However, the flows and water levels of Chiang Saen and Luang Prabang in 2018 were lower than that of 2008-2017 average. The infilling and thereby low discharge from upstream dams during that year could have caused this anomaly. The reduction in rainfall in 2018 is greatly felt in the central and eastern LMB leading to drop in flows and levels in corresponding stations.

The year 2019 saw deficient rainfall when compared to 2008-2017 average, except for four months (Figure C-2). Most parts of the LMB received below normal rainfall during the early months of the wet season leading to low flows in the LMB. Severe reduction in rainfall (reduction of 200 mm to above 400 mm) occurred in stations between Xayaburi and Mukdahan in July. Though above average rainfall conditions are observed in August, deficient rainfall conditions prevailed in these stations thereafter. It is clear from Figure C-2 that rainfall anomaly played an important role in the causation of low flows and drought in the LMB region.

From Figure C-3, the reduction of rainfall as compared to 2008-2017 average has continued to 2020, with all the months except October experiencing very low rainfall. The rainfall anomaly was very high in July, when almost all parts of the LMB saw severe reduction in rainfall compared to the long-term average. As in 2019, major stations ranging from Chiang Saen to Stung Treng and the Tonle Sap Lake region showed rainfall reduction of more than 400 mm in 2020 relative to 2008-2017. The increase in rainfall in October alone was not enough to restore normal flows and levels at different stations along Mekong and thus leading to one of the worst droughts recorded in recent decades.

The deficient rainfall continued to January 2021 though February marked an increase from 2008-2017 average (Figure C-4). As in 2020, the months leading up to wet season mark a reduction in rainfall, especially in northern parts of the LMB. Vientiane and surrounding areas show the greatest rainfall anomaly (negative) for consecutive months in 2021. The rainfall conditions improve in September and October, except in Nong Khai region.

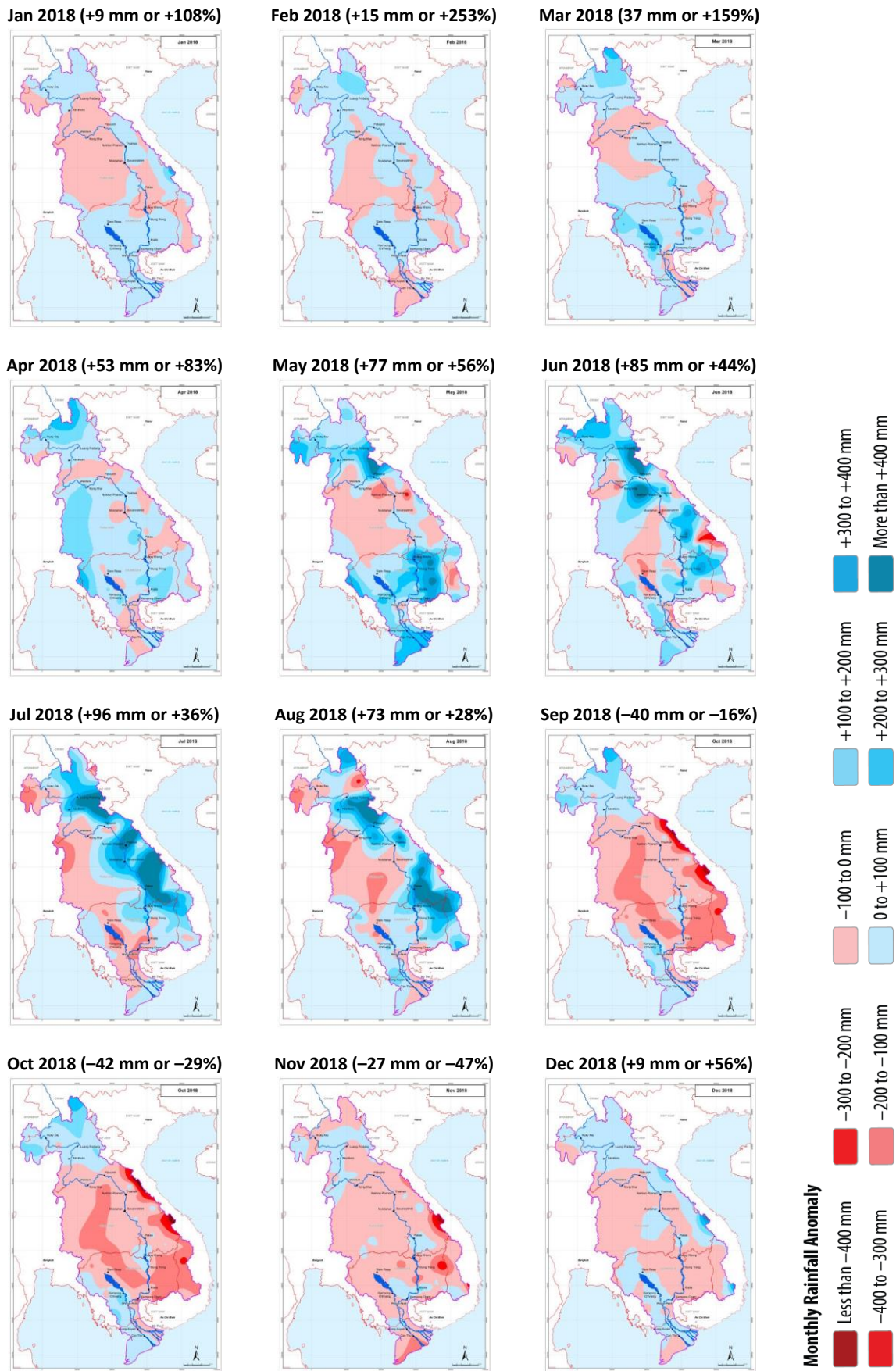


Figure C-1. Anomaly of monthly rainfall for 2018 , compared to average of 2008-2017. Amount of rainfall presents in mm and ratio is in %.

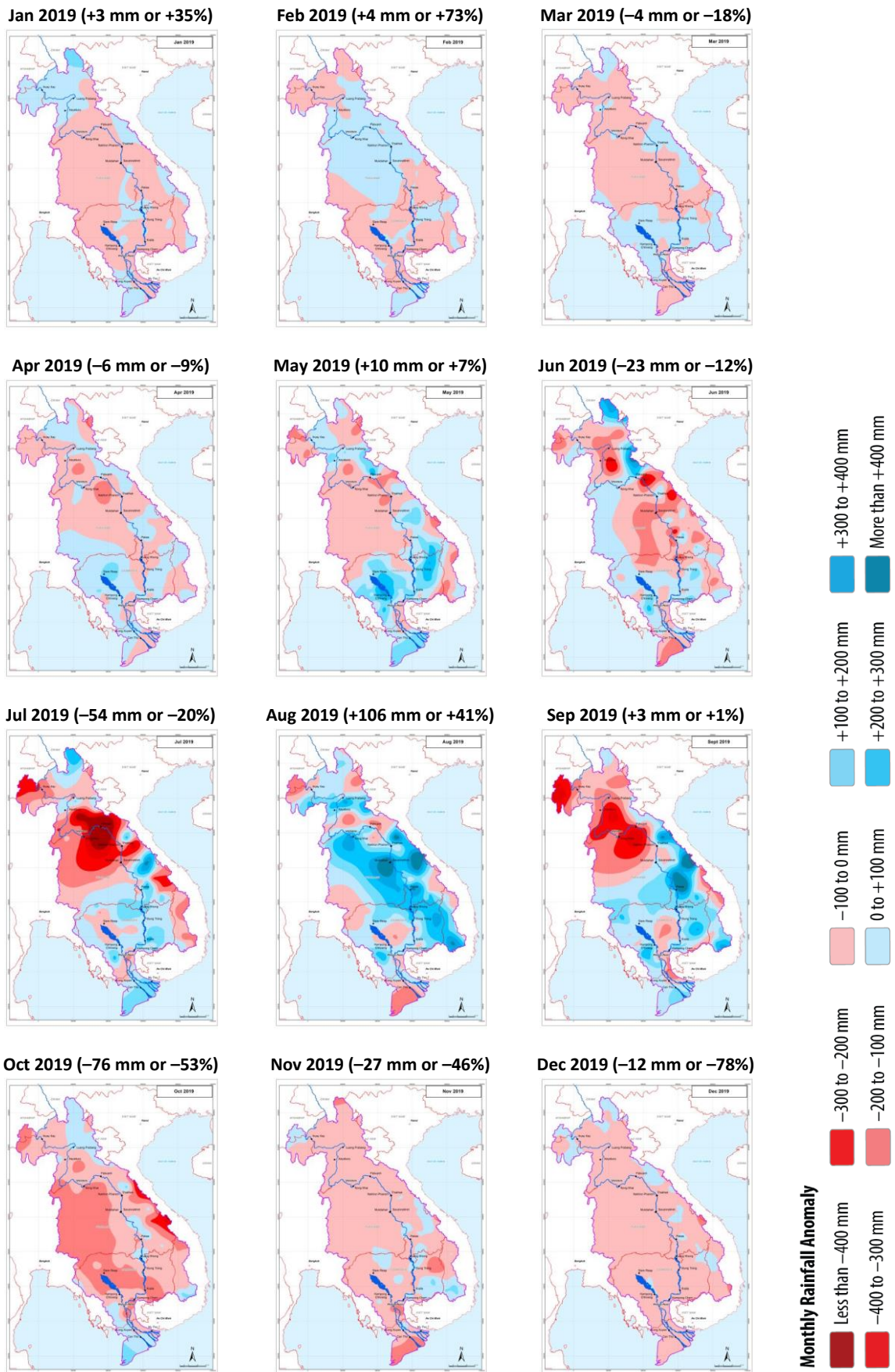


Figure C-2. Anomaly of monthly rainfall for 2019, compared to average of 2008-2017. Amount of rainfall presents in mm and ratio is in %.

Jan 2020 (-6 mm or -73%)



Feb 2020 (-5 mm or -84%)



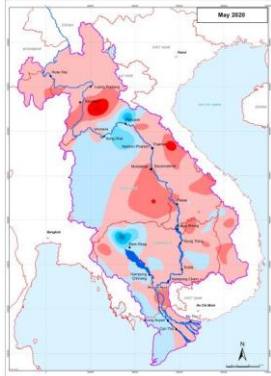
Mar 2020 (-9 mm or -39%)



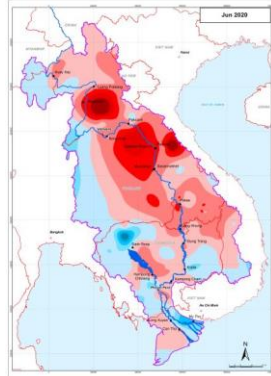
Apr 2020 (-26 mm or -41%)



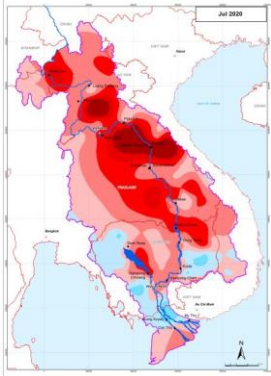
May 2020 (-37 mm or -27%)



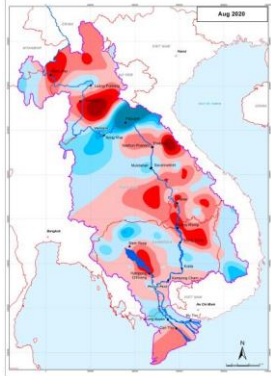
Jun 2020 (-68 mm or -36%)



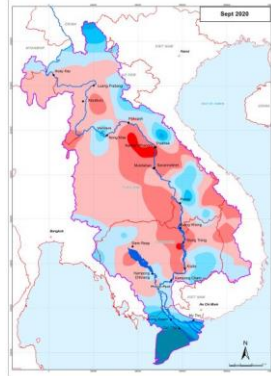
Jul 2020 (-149 mm or -56%)



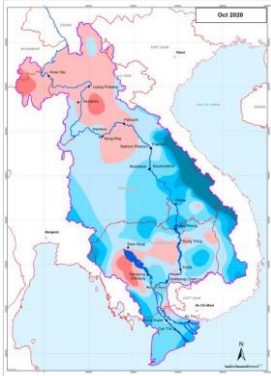
Aug 2020 (-26 mm or -10%)



Sep 2020 (-8 mm or -3%)



Oct 2020 (+116 mm or +81%)



Nov 2020 (-19 mm or -33%)



Dec 2020 (-5 mm or -34%)

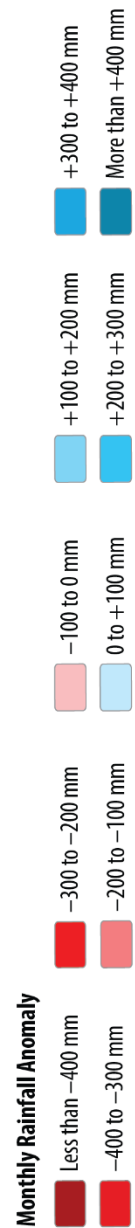


Figure C-3. Anomaly of monthly rainfall for 2020, compared to average of 2008-2017. Amount of rainfall presents in mm and ratio is in %.

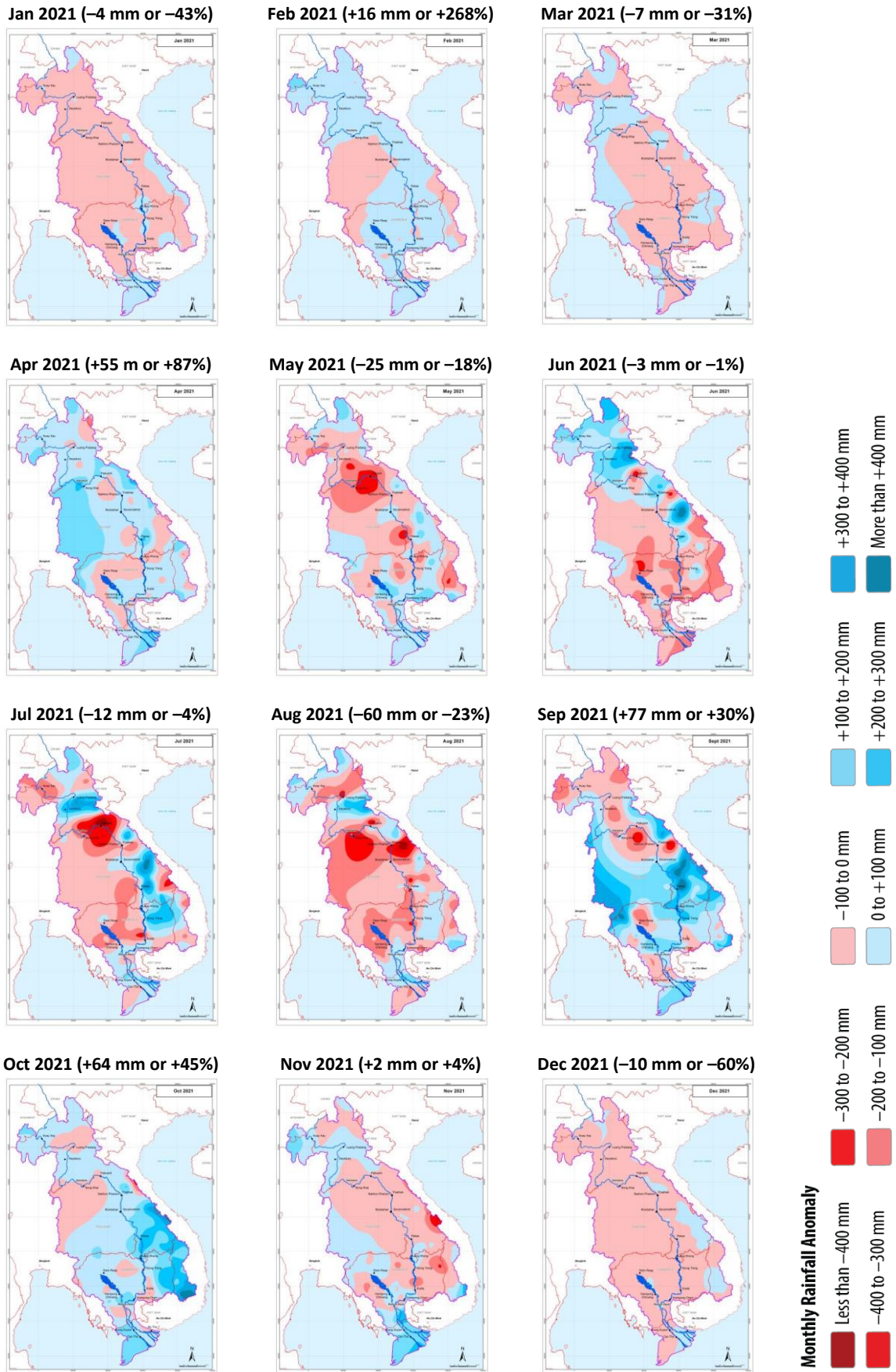


Figure C-4. Anomaly of monthly rainfall for 2021, compared to average of 2008-2017. Amount of rainfall presents in mm and ratio is in %.

Annex D: Standardised Precipitation Index and Combined Drought Index for 2018-2021

The MRC is currently investigating a range of drought indexes for the LMB, including Standardised Precipitation Index (SPI), Standardised Runoff Index (SRI), Soil Moisture Deficit Index (SMDI), Combined Drought Index (CDI), Dry Spell, Root Zone Soil Moisture and Drought severity²⁴. There is no single index that can be used to define management measures for all types of drought given the number and variety of sectors affected. The preferred approach is to use different indices with different combinations of inputs.

The anomaly maps for the SPI and CDI are presented on the following pages. The SPI is recommended by the World Meteorology Organisation (WMO)^{25,26}. It provides information on short and long-term meteorological drought. It is determined by precipitation over 1, 3, 6 and 12 months. The CDI²⁷ is the main index representing a global state of the meteorological, hydrological and agricultural indices. It is a combination of three indices of SPI, SRI and SMDI with different weights according to the importance of the conditions where SMDI is more important perceptually than SPI and SRI as these last two variables are similar in their behaviour in comparison to SMDI.

²⁴ Further details of the MRC Drought Monitoring and Forecasting System can be found in the Technical Report of the Lower Mekong Basin (LMB) drought monitoring and forecasting system, September 2019.

²⁵ SPI is a dimensionless index varying between -3 to 3 and ranging in the following stretch of conditions: Extremely dry for $SPI < -2$; Very dry for $-2 \leq SPI < -1.5$; Moderately dry for $-1.5 \leq SPI < -1$; Near normal for $-1 \leq SPI < 1$; Moderately wet for $1 \leq SPI < 1.5$; Very wet for $1.5 \leq SPI < 2$; and Extremely wet for $2 \leq SPI$.

²⁶ SPI calculation is derived from the Regional Hydrologic Extremes Assessment System (RHEAS) hydrologic nowcast and forecast framework. RHEAS is a modular hydrologic modeling framework that has been developed at the United States National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL). "The nowcasting simulations are constrained by assimilating a suite of Earth Science satellite observations, resulting in optimal estimates of directly and indirectly observed water variables" (Andreadis, 2018). Additionally, RHEAS is under a PostGIS database that works based on a PostgreSQL database storing the spatial information to run the model including internal conditions and parameters. It is composed by two models, VIC (Variable Infiltration Capacity Macroscale Hydrologic) and DSSAT (Decision Support System for Agrotechnology Transfer) models. VIC is a hydrologic model that solves physical equations to transform meteorological conditions into hydrological conditions while DSSAT takes the processed hydrological conditions and transform them into agricultural conditions.

²⁷ CDI is a dimensionless index varying between -3 to 3 and ranging in the following stretch of conditions: Exceptional drought for $CDI < -2.5$; Extreme drought for $-2.5 \leq CDI < -2$; Severe drought for $-2 \leq CDI < -1.5$; Moderate drought for $-1.5 \leq CDI < -1$; and Normal condition for $CDI \geq -1$.

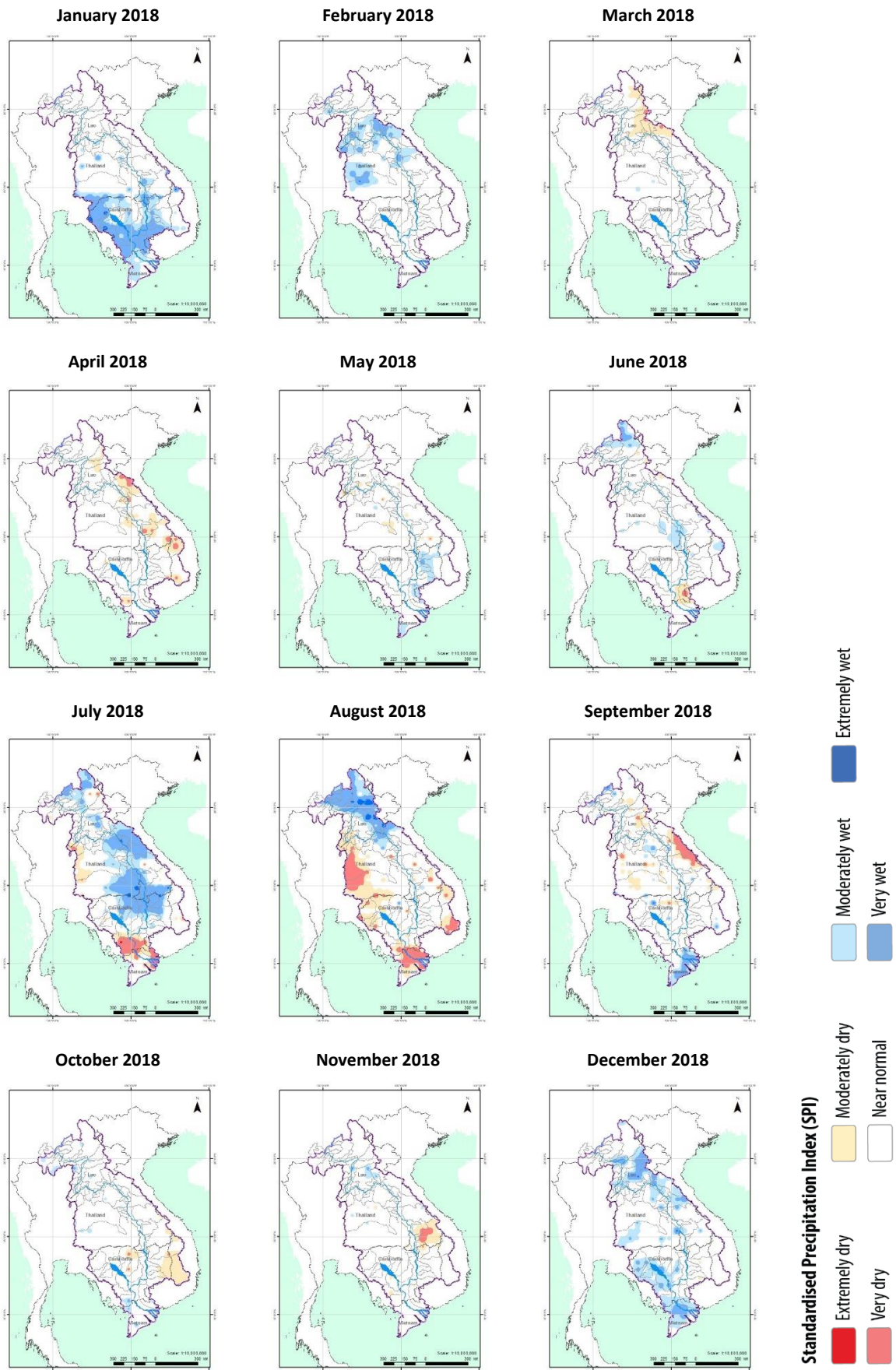


Figure D-1. Standardised Precipitation Index (SPI) for 2018 in the Lower Mekong Basin.

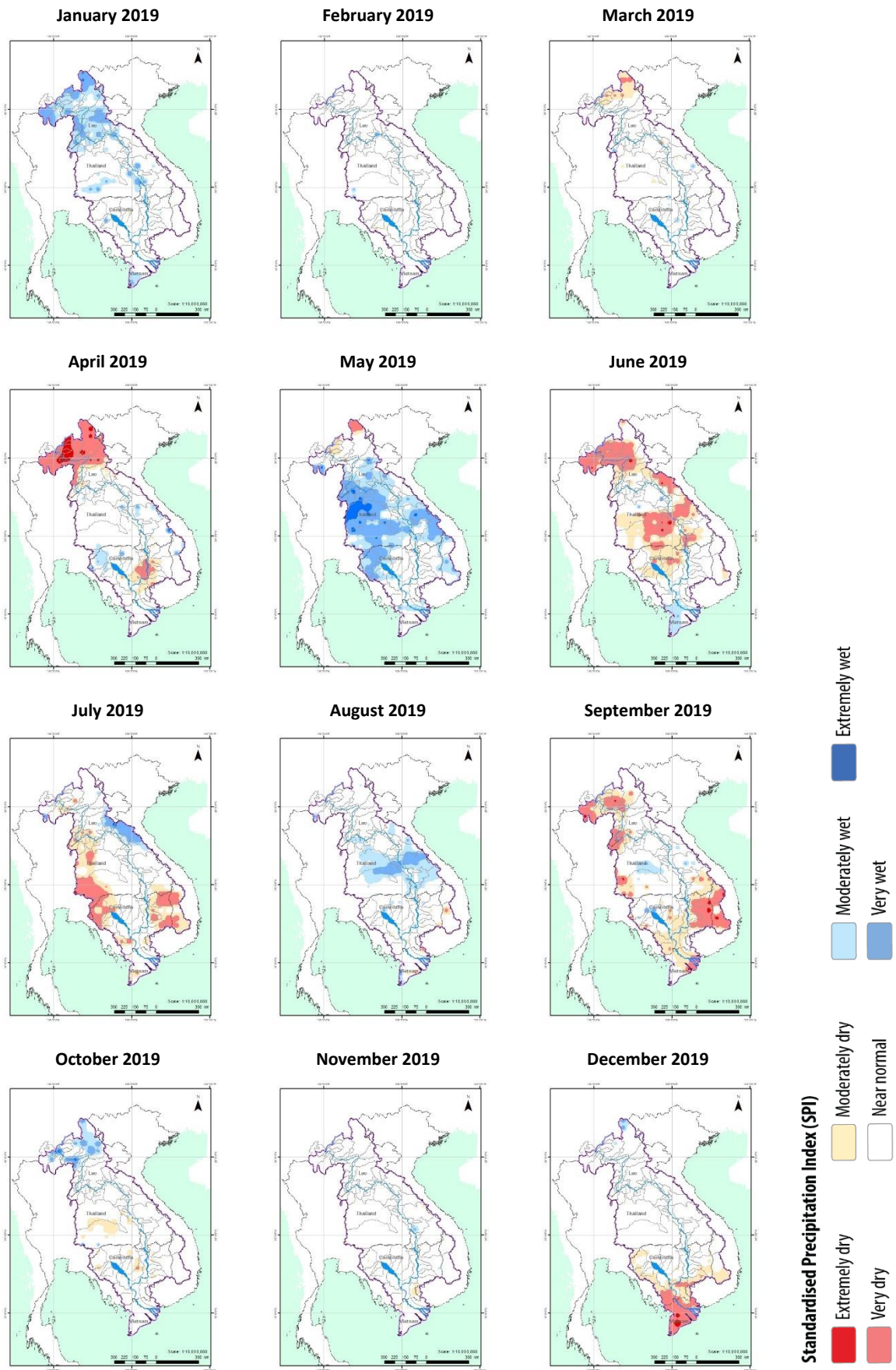


Figure D-2. Standardised Precipitation Index (SPI) for 2019 in the Lower Mekong Basin.

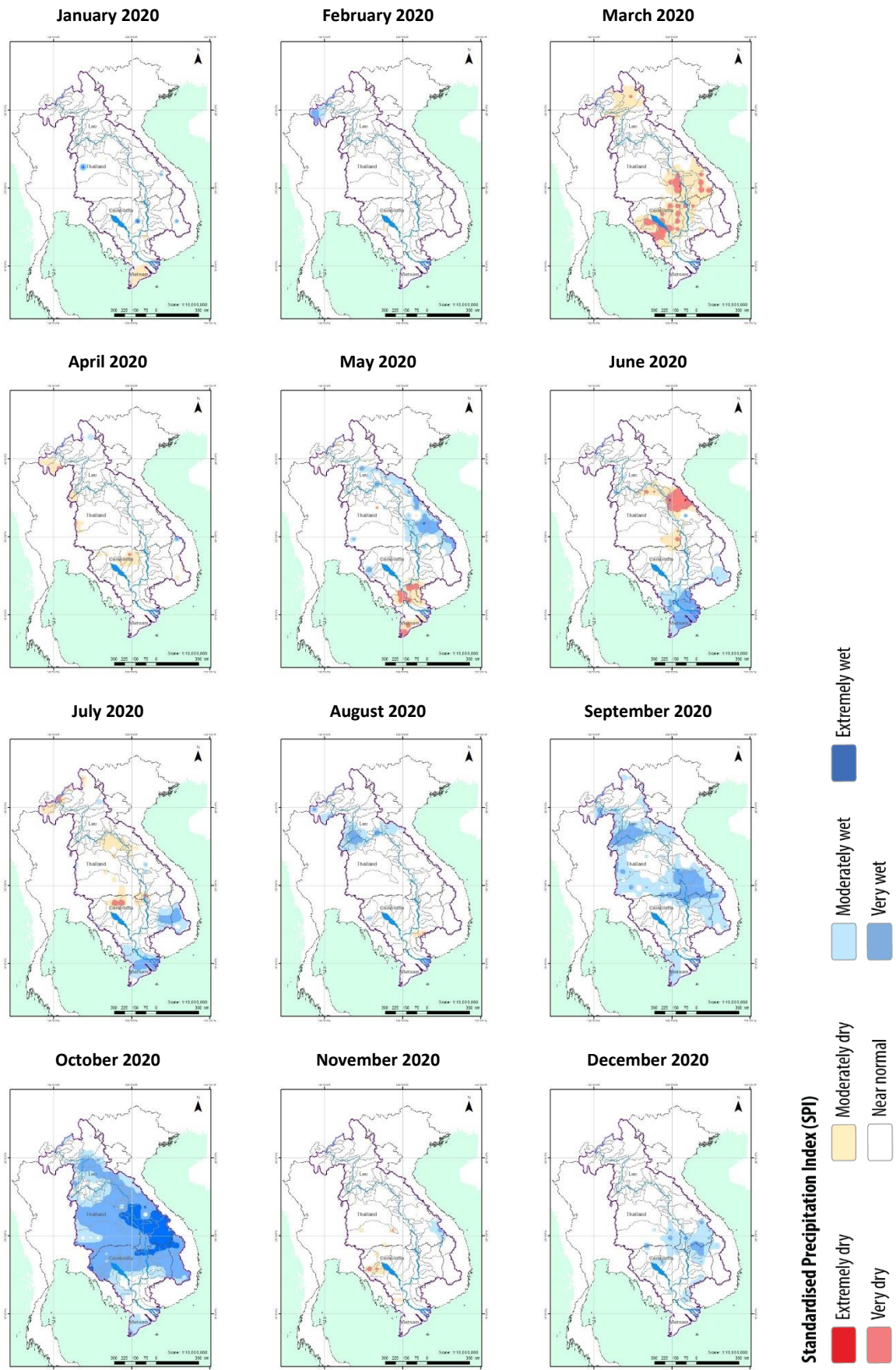


Figure D-3. Standardised Precipitation Index (SPI) for 2020 in the Lower Mekong Basin.

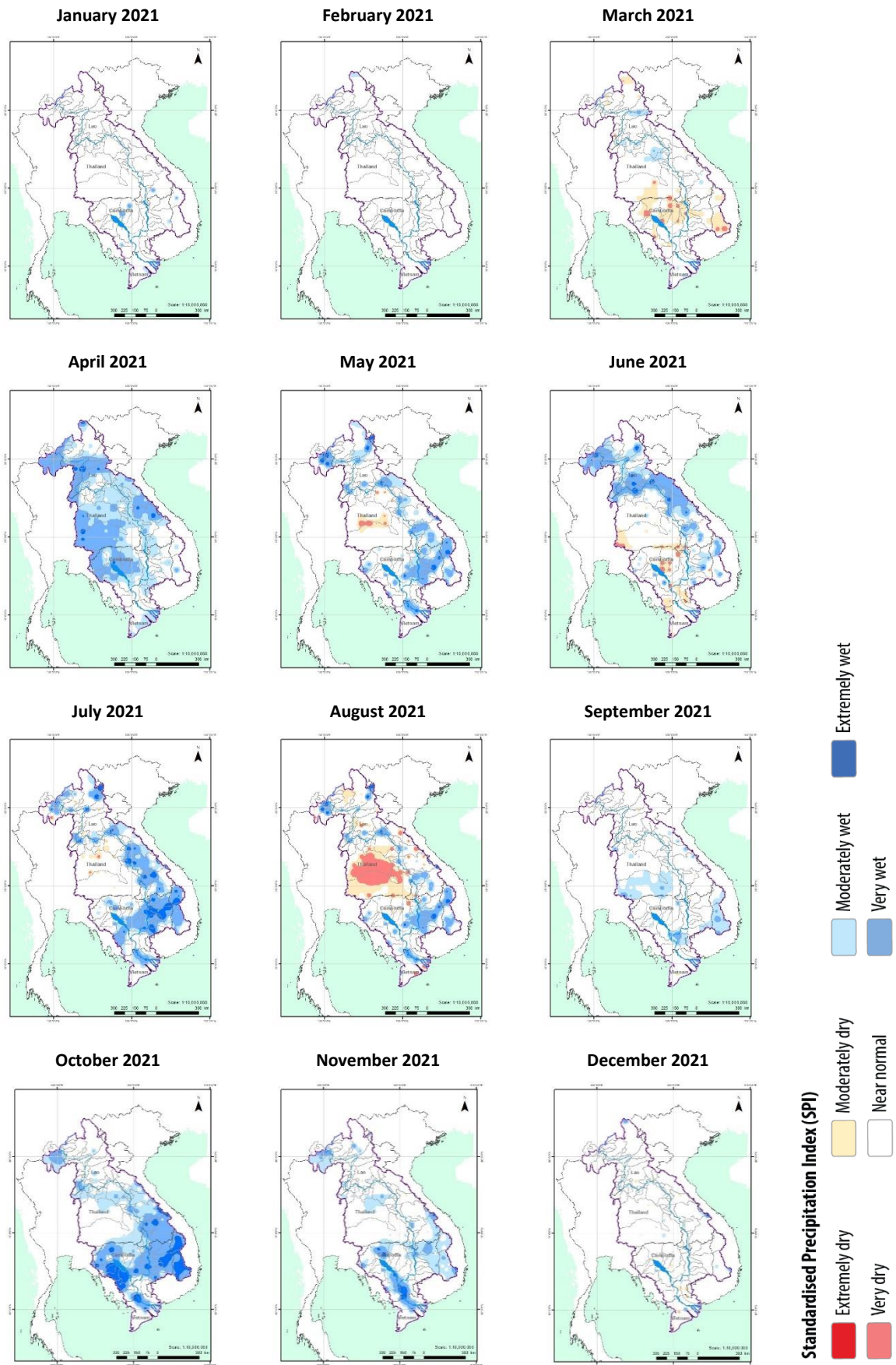


Figure D-4. Standardised Precipitation Index (SPI) for 2021 in the Lower Mekong Basin.

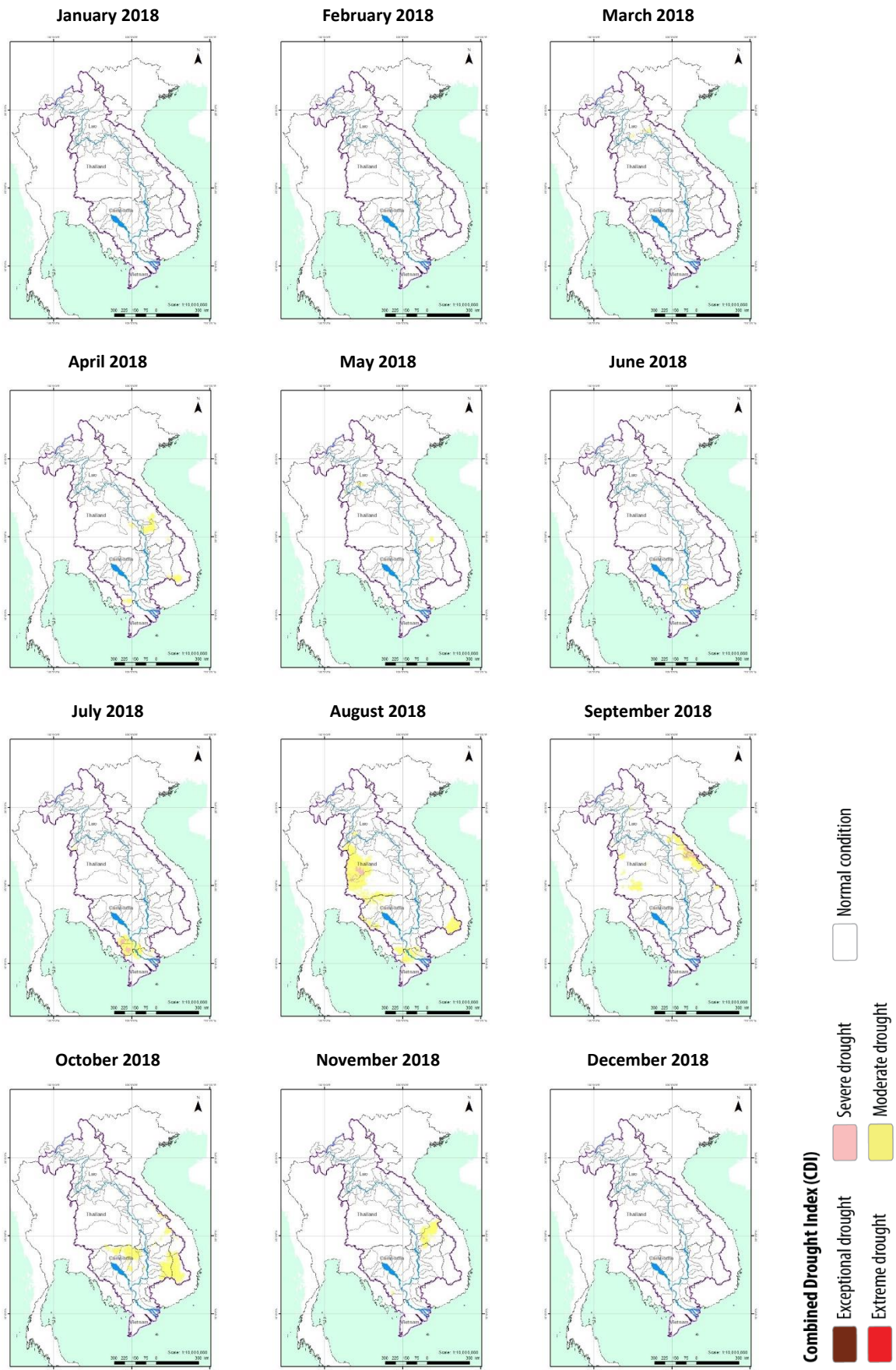


Figure D-5. Combined Drought Index (CDI) for 2018 in the Lower Mekong Basin.

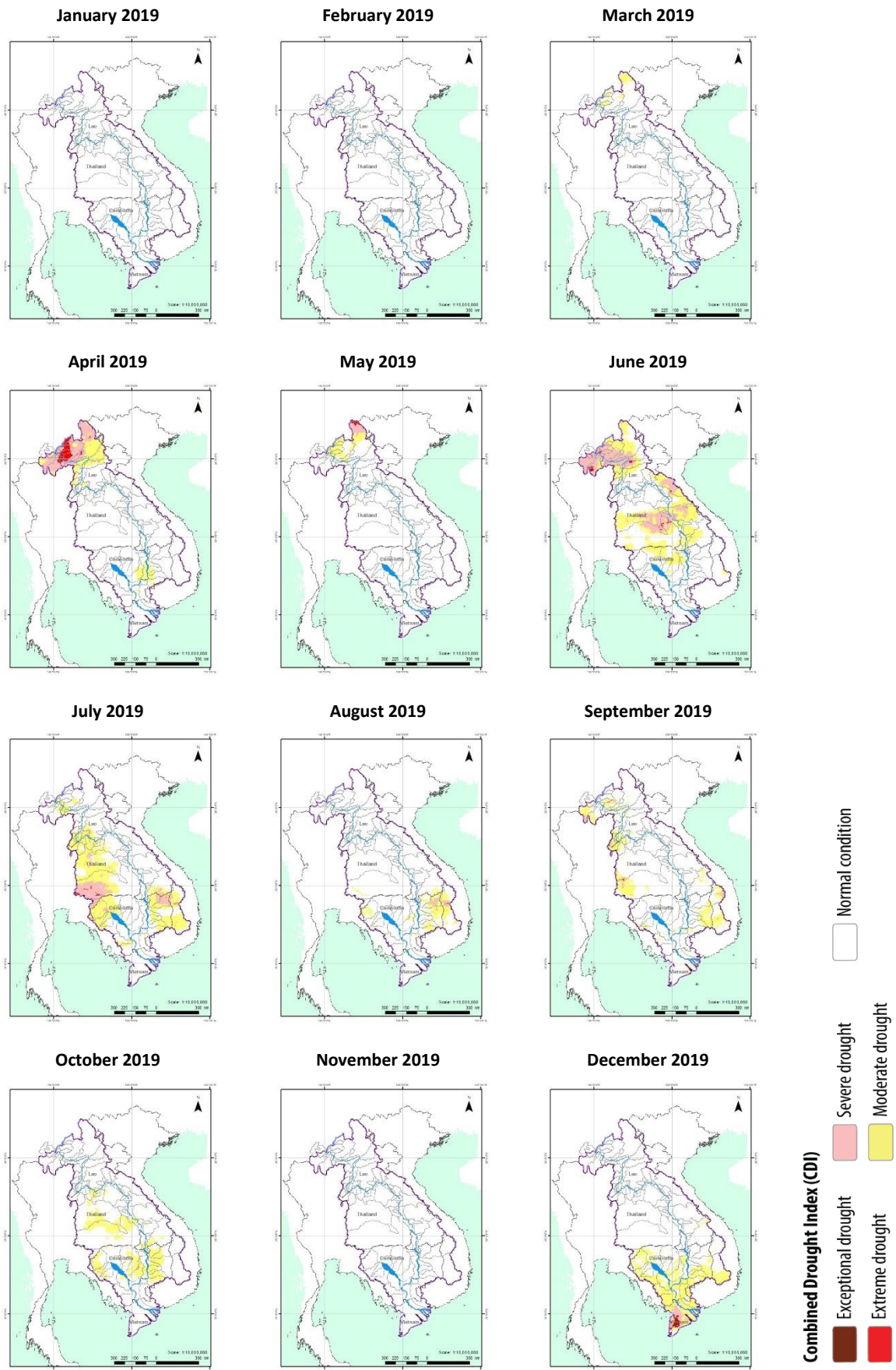


Figure D-6. Combined Drought Index (CDI) for 2019 in the Lower Mekong Basin.

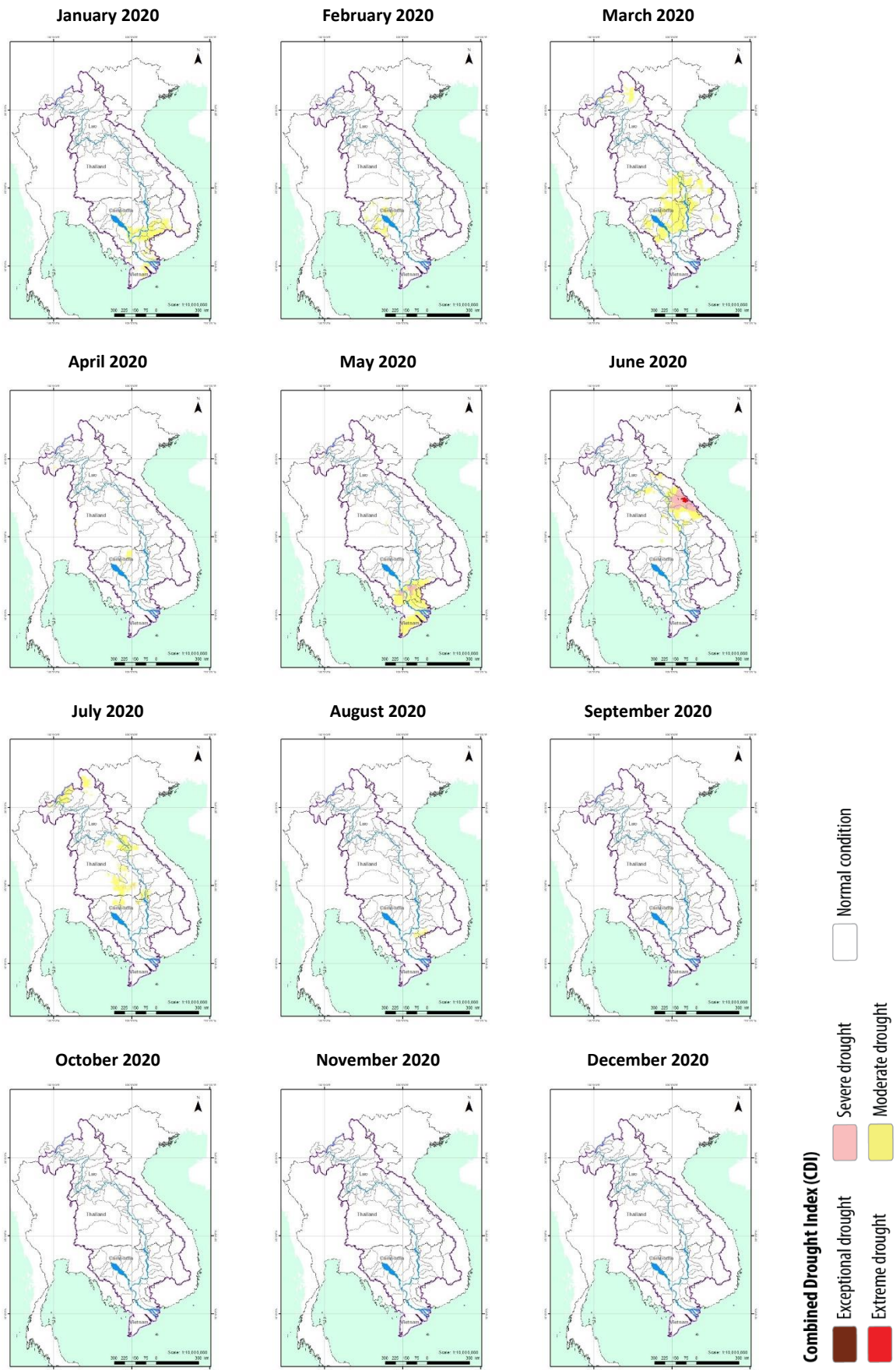


Figure D-7. Combined Drought Index (CDI) for 2020 in the Lower Mekong Basin.

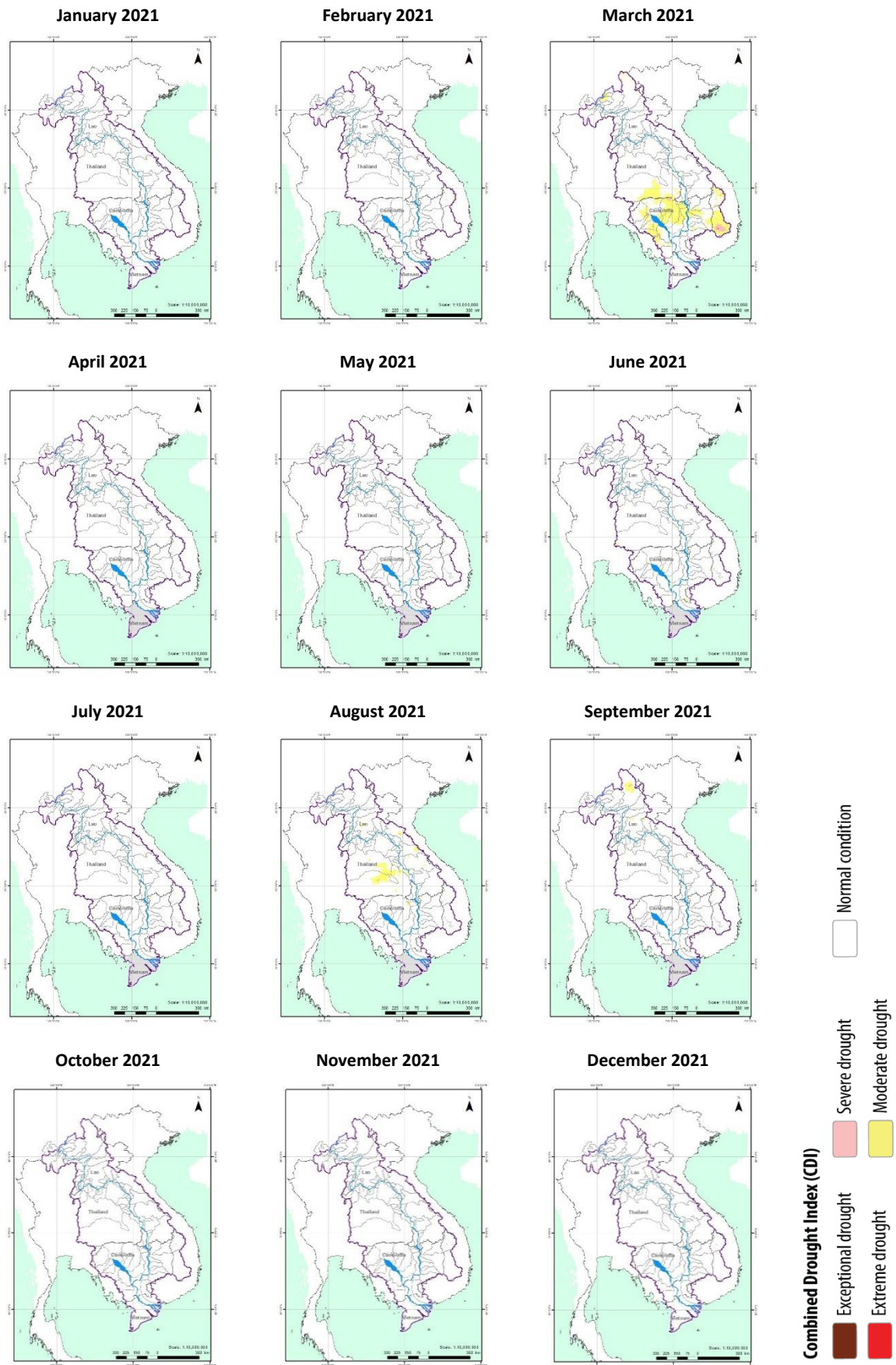


Figure D-8. Combined Drought Index (CDI) for 2021 in the Lower Mekong Basin.

Annex E: Characteristics of water level of the Mekong mainstream for 2018-2021

The influence of the storage in the UMB can be captured in the immediate downstream station at Chiang Saen. The stations further downstream of Chiang Saen gradually pick up the flows because of the contribution from tributaries. The 2019-2020 drought seems to have occurred mostly due to the low and delayed rainfall during those years when compared to the 2018 discharge trend.

The lowest flows occurred during the period of 2019 and 2020, leading to severe droughts. For the Jinghong and Chiang Saen stations, the 2019 and 2020 flows are seemingly similar, while for Nong Khai, the 2020 flows are slightly higher than that of 2019. For the other downstream stations, the lowest flows occurred in 2020. For Pakse and Stung Treng, a sharp rise in flows equal to historic levels is observed between September and October 2019. This sharp rise and fall of flows in 2019 possibly show the impacts of delayed onset and premature return of rainfall in the downstream stations starting from Pakse. The low flows continued to 2020 and 2021 (until October).

The impact of upstream dams is less evident in the case of stations like Nakhon Phanom, Mukdahan, Pakse and Stung Treng, could be because of flow contribution from tributaries. In Nakhon Phanom and Mukdahan stations, the flow for the year 2018 reaches the same peaks as that of historical and 2008-2017 trends. However, the duration of peak flows has reduced from about five months (June to October) to around four months (July to October) for 2018 and subsequent years for the five stations (from Nong Khai to Stung Treng). Furthermore, it is evident that the peak flows are delayed for the years 2018, 2019, 2020 and 2021.

The dry season water levels in the recent years are higher than the historical and 2008-2017 averages for most of the downstream stations. This leads to the inference that the upstream dams are releasing water during dry periods. During the wet period, the water levels at all stations are lower in 2019, 2020 and 2021 when compared to 2008-2017. In some stations such as Pakse and Stung Treng, the 2019 water level raises above the historical peaks, but for a shorter period. However, the general trend of reduced water levels for the years post 2018 when compared to 2018 levels (when most of the large dams came online) indicates the lack of rainfall. The short duration water level peak observed downstream of Mukdahan station in September 2019 gives a hint about the high rainfall received in the lower reaches of the LMB.

The peak water levels for the last four stations (Figure 11) are generally delayed by a month when compared to the upstream stations. In these stations, especially for Phnom Penh Port and Kampong Luong stations, the peak water levels continue to December and the descend starts by January next year. In Phnom Penh Port station, though the 2019 level reaches the 2018 peak, the former is short lived. The short duration peaks are also observed in further downstream stations, when compared to 2018, indicating the lower rate of rainfall received. The 2019 drought continued to 2020 as evident from the water levels. The water levels in 2020 at Pakse and further downstream stations are lower than that in 2019 and the levels peak around November in 2020.

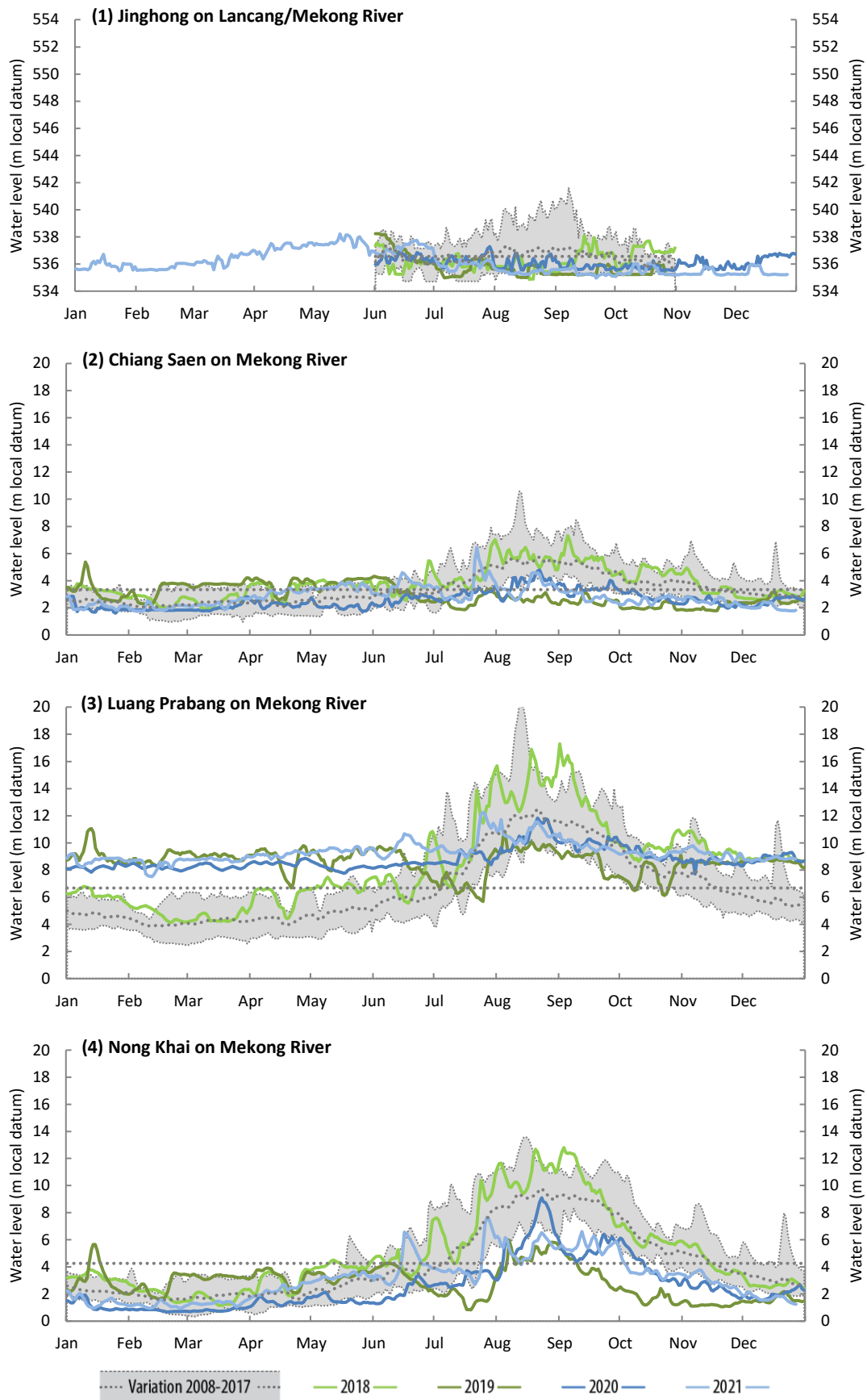


Figure E-1. Characteristics of water level of the Mekong mainstream at (1) Jinghong, (2) Chiang Saen, (3) Luang Prabang, (4) Nong Khai, compared to conditions of 2008-2017. See location in Figure 6.

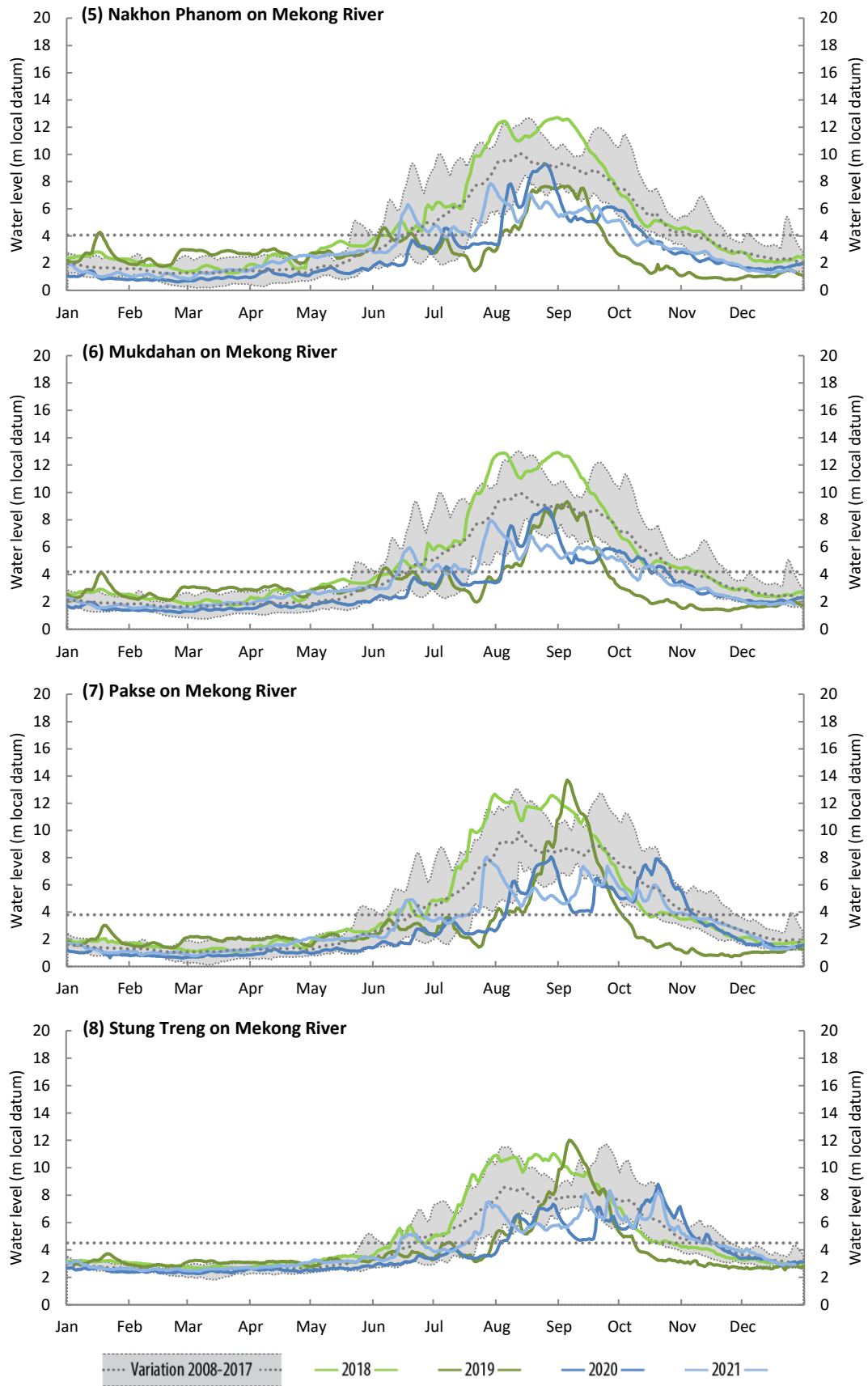


Figure E-2. Characteristics of water level of the Mekong mainstream at (5) Nakhon Phanom, (6) Mukdahan, (7) Pakse and (8) Stung Treng, compared to conditions of 2008-2017. See location in Figure 6.

Annex F: Quarterly global temperature anomaly for 2018-2021

The anomalies of the land/sea surface temperature²⁸ benchmark the changes in the Mekong against global changes. Quarterly average temperatures for 2018-2021 were compared to the average of the base period of 2008-2017.

The higher temperature in 2019-2020 was noted on the global scale. More specifically, the temperature anomaly for the Mekong region suggests that 2019-2020 were hot dry years. The year 2018 tends to be a normal year; however, the last quarter of 2018 tends to be hotter than usual. Both temperature and rainfall for the Year 2021 vary between the average of 2008-2017.

²⁸ The land surface temperature is based on GISS analysis based on GHCN v4 while the sea surface temperature uses NOAA/NCEI's Extended Reconstructed Sea Surface Temperature (ERSST) v5 (NASA, 2022). Anomalies is the mean temperature averaged over a specified mean of the base period of 2008-2017 with a smoothing radius of 250 km (NASA, 2022).

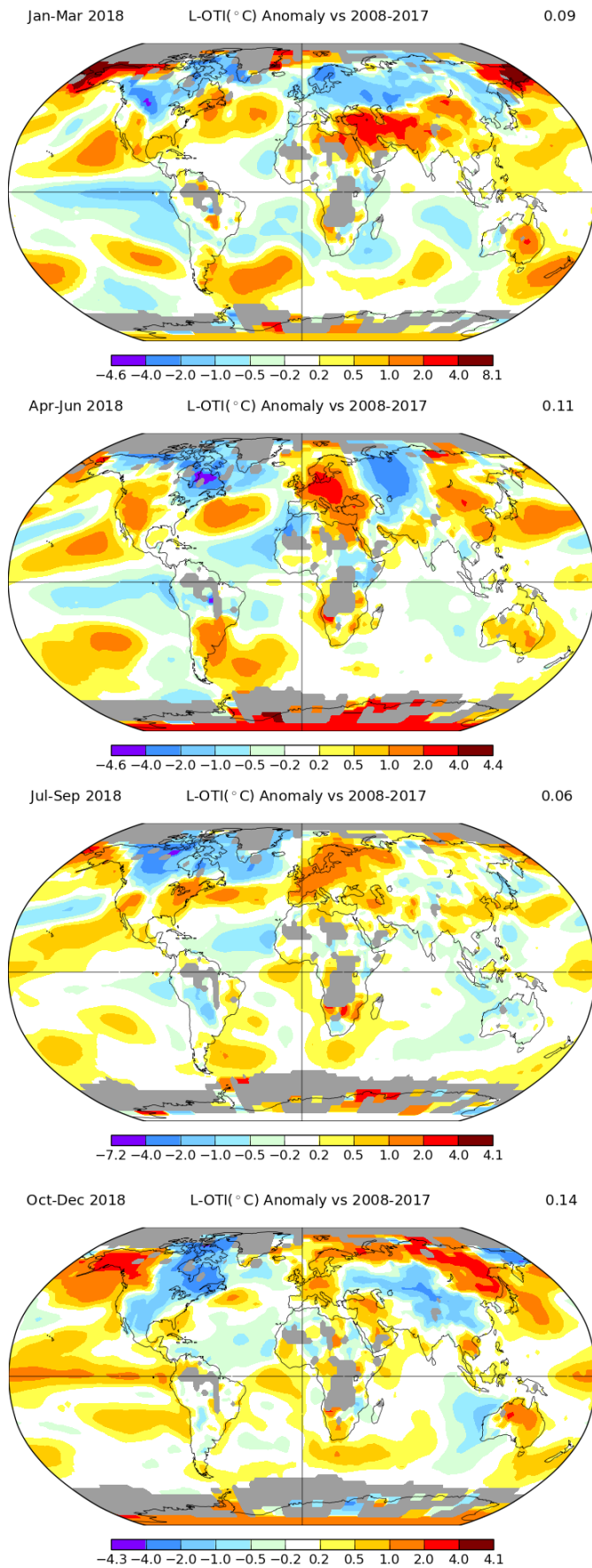


Figure F-1. Quarterly global temperature anomaly for 2018, compared to the base period of 2008-2017.

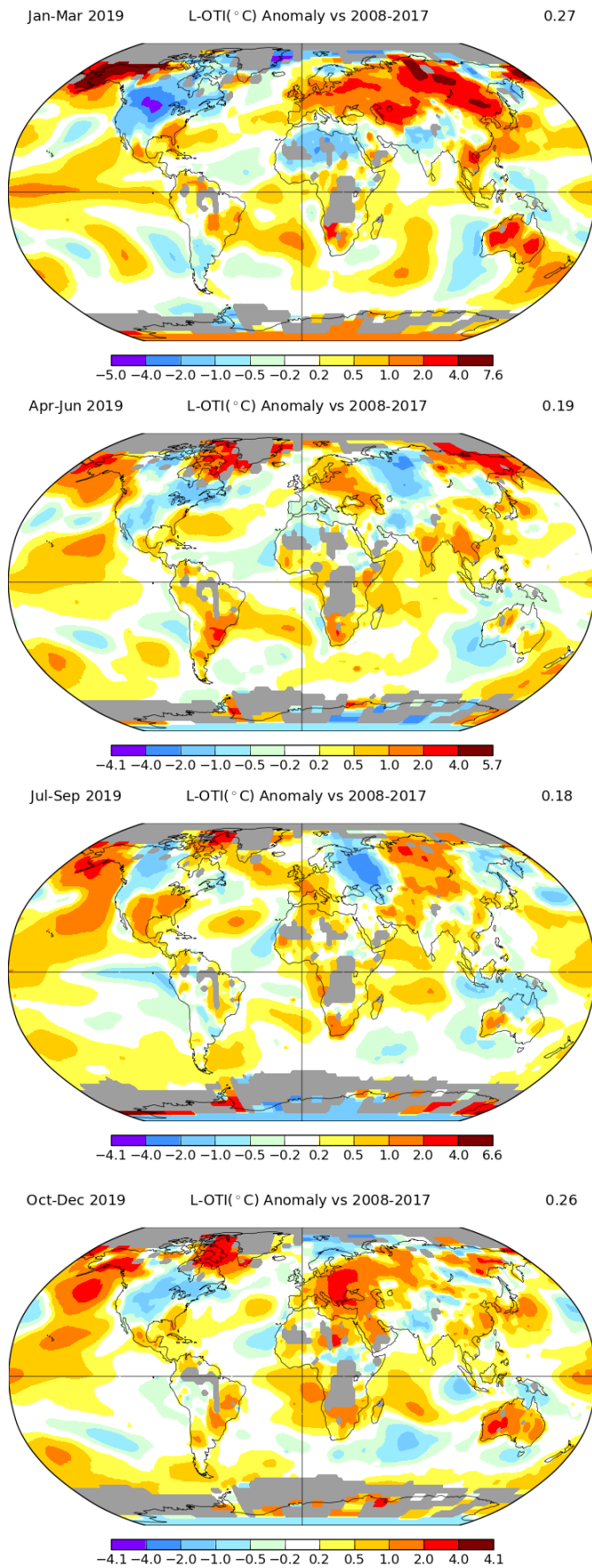


Figure F-2. Quarterly global temperature anomaly for 2019, compared to the base period of 2008-2017.

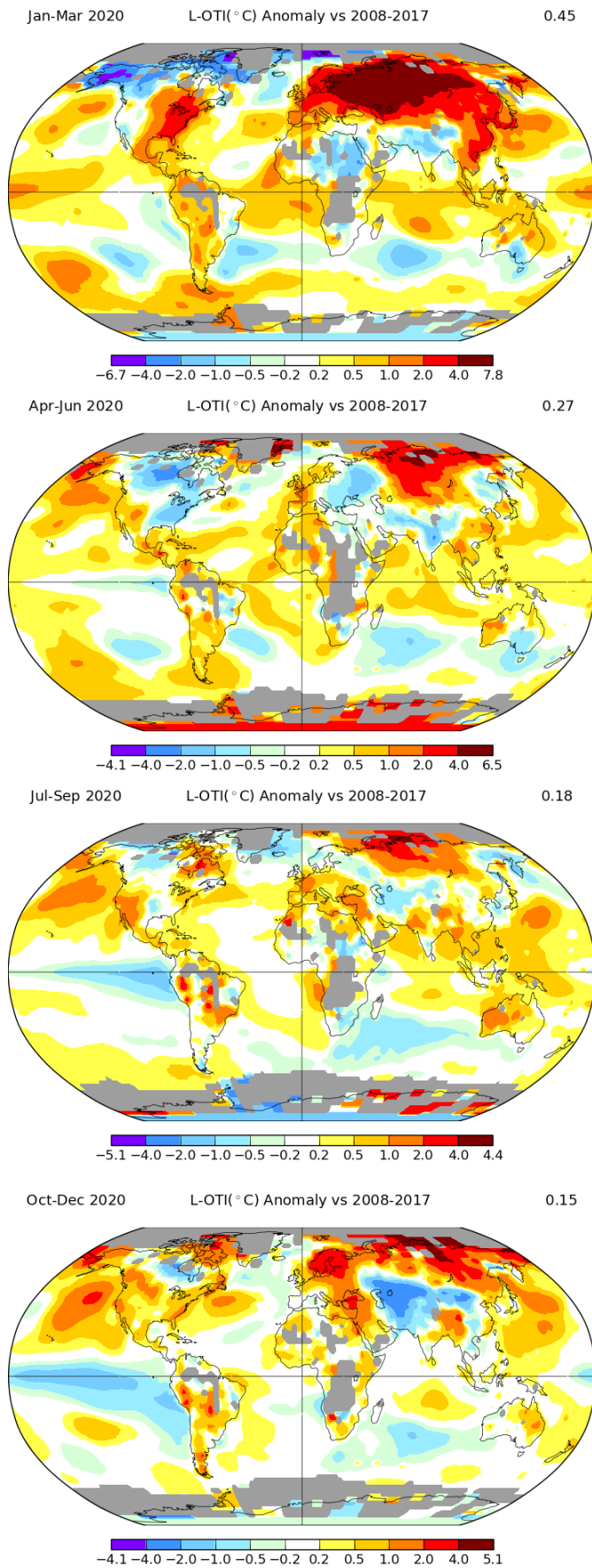
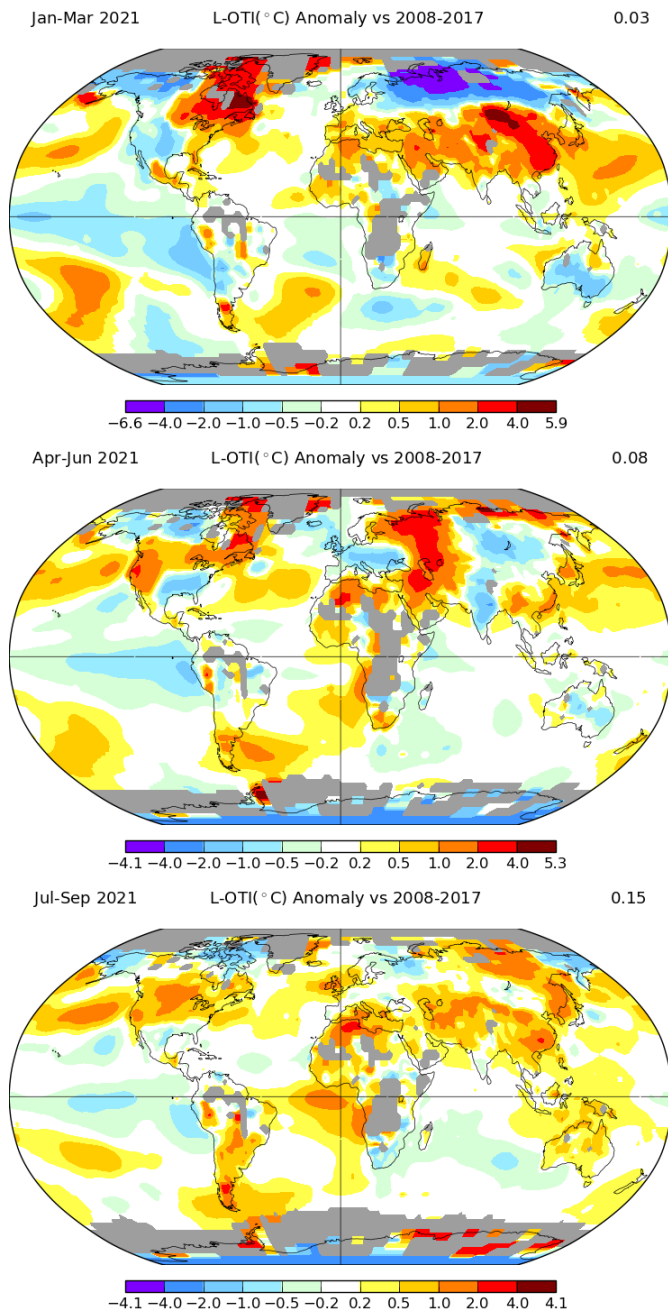


Figure F-3. Quarterly global temperature anomaly for 2020, compared to the base period of 2008-2017.



No data for October-December 2021 at the time of publication.

Figure F-4. Quarterly global temperature anomaly for 2021, compared to the base period of 2008-2017.



Mekong River Commission Secretariat

P. O. Box 6101, 184 Fa Ngoum Road, Unit 18 Ban Sithane Neua,
Sikhottabong District, Vientiane 01000, Lao PDR
Tel: +856 21 263 263. Fax: +856 21 263 264
www.mrcmekong.org

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