Lancang-Mekong Cooperation Special Fund Projects

Forecasting and Analysis of Future Trends of Mekong Water Resources

生态环境部对外合作与交流中心
Foreign Environmental Cooperation Center

澜沧江－湄公河环境合作中心
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Contents

Chapter 1 Background

The Lancang-Mekong River is an important transboundary river in South East Asia and beyond. It has a sound aquatic environment with abundant water resources. Connected by the river, the riparian countries share cultural similarities, and rise and thrive along the river. Water resources serve as an important material basis for the development of riparian countries.

In March 2016, the six riparian countries, including China, Cambodia, Laos, Myanmar, Thailand, and Vietnam, jointly established the Lancang-Mekong Cooperation (LMC) mechanism, in order to promote sustainable social and economic development in the whole basin and put into practice the Belt and Road Initiative. Water resources and environmental protection are among the five priority areas and are of particular importance for advancing the LMC overall. At the two LMC Leaders' Meetings and the three LMC Foreign Ministers' Meetings, the riparian countries expressed a strong desire to cooperate in water resources, hoping to support sustainable social and economic development with sustainable use of water resources through reciprocal cooperation between upstream and downstream. While maintaining regional ecological security, such cooperation will drive the implementation of water-related goals under the United Nations 2030 Agenda for Sustainable Development and the ASEAN Community Vision 2025.

In recent years, due to multiple factors such as climate change and human activities, the hydrological situation and water environment of the Lancang-Mekong River has exhibited heterogeneous changes. The temporal and spatial distribution and variance of water resource elements such as precipitation, runoff, and water quality have all changed. In general, global warming has intensified the differentiation of precipitation variance in the basin, leading to an increase in the frequency and extent of extreme weather events in recent years. The resulting floods have seriously damaged the lives and property of people in the basin. At the same time, the utilization rate of water resources and hydropower resources in the entire basin has increased year by year. Among the riparian countries, Laos will accelerate the pace of hydropower development, planning to reach a scale of about 70% of the total installed capacity of the basin. Thailand mainly will use more of Mekong water resources in the future, mainly for the purpose of agricultural irrigation. Both Cambodia and Vietnam have developed hydropower plans for the mainstream and tributaries of the Mekong River. For the sake of soil fertility of the floodplains, Cambodia has a large demand for the peak flow of the Mekong River during the rainy season. With the largest irrigation area in the Mekong River Basin, Vietnam needs more water for irrigation in the Mekong Delta during the dry season. In the light of this, the contradictions in the supply and demand of water resources between the upper and lower reaches of the Lancang-Mekong River become increasingly prominent. The future trend of water resources in the basin will exert a significant impact on regional economic and social development and the overall diplomatic situation for the LMC mechanism. In order to further deepen LMC in water resources and the environment, it is necessary to collect and collate data on water resources such as precipitation and water quantity and quality in the Lancang-Mekong River in the past decade, laying a solid foundation for further analyzing and forecasting the water resource situation and sharing data between the upstream and downstream countries in the basin.

Using methods such as data source identification and statistical analysis, this study collects information from the Mekong River Commission (MRC), World Bank, and Asian Development Bank (ADB), as well as the water resource bulletins and related databases of the five Mekong countries, and conducts trend and correlation analysis of data on water resources and water environment. Combined with literature review, future trends of water resources in the basin are forecasted, and changes in regional management policies are analyzed. On this basis, relevant recommendations are offered.

Chapter 2 Overview of the Lancang-Mekong River Basin

The Lancang-Mekong River originates from Yushu Tibetan Autonomous Prefecture, Qinghai Province, China. The mainstream meanders from north to south through China, Myanmar, Thailand, Laos, Cambodia, and Vietnam before emptying into the sea in the west of Ho Chi Minh City, Vietnam. It is called the Lancang River in Tibet and Yunnan, China, and the Mekong River after flowing out of Yunnan to the sea. The drainage area covers vast geographical and climatic zones, and stands among the most biodiverse regions in the world. The Lancang-Mekong River supplies natural resources for the socio-economic development of riparian countries, so it is crucial for the survival, life, and production of the 60 million people living in the basin.

2.1 Geographical characteristics

The Lancang-Mekong River is a typical north-south river running through all natural landscapes except the desert. The shape of drainage area and the distribution of water system are complex and changeable under the control of the longitudinal and latitudinal tectonic systems. The Lancang River Basin includes southern Qinghai, eastern Tibet, and southwestern Yunnan, and gradually slopes from the north to the south, with broom-shaped water system. The Mekong River Basin includes four geographic areas: the Northern Uplands, the Khorat Plateau, the Tonle Sap Basin, and the Mekong Delta. The elevation map of the Lancang-Mekong River Basin is as shown below.

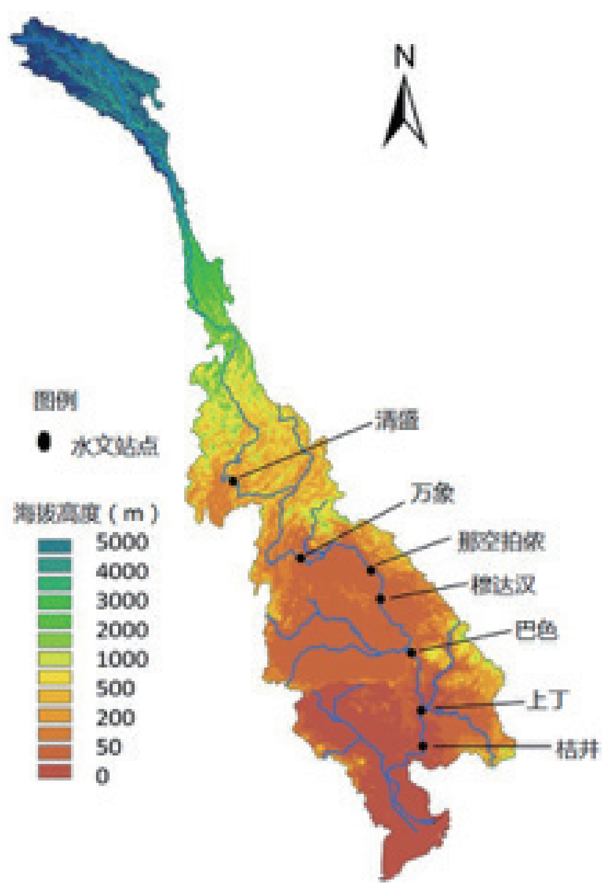

Figure 1 Elevation map of the Lancang-Mekong River Basin

2.2 Climate characteristics

The Lancang-Mekong River Basin is situated in the subtropical/tropical monsoon region and affected by the monsoon climate. The wet and dry seasons are distinct, and rainfall is very unevenly distributed throughout the year as well as in space. Due to the impact of terrain, southwestern monsoon, and northeastern tropical cyclone across China and Vietnam, the annual precipitation exceeds 3,000 mm in the central part of northern Laos, while it is less than 1,000 mm in the arid region of northeast Thailand. The uneven spatial and temporal distribution of precipitation has led to frequent flood and drought disasters. The specific spatial distribution of precipitation is as shown in the figure below.

Temperature changes moderately in the Lancang-Mekong River Basin, with an average ranging from 25 to 27°C. Average relative humidity in the atmosphere peaks at slightly greater than 80% in September and hits the lowest of about 60% in March. Evapotranspiration varies widely during the year, reaching 80 mm in July and 160 mm in June.

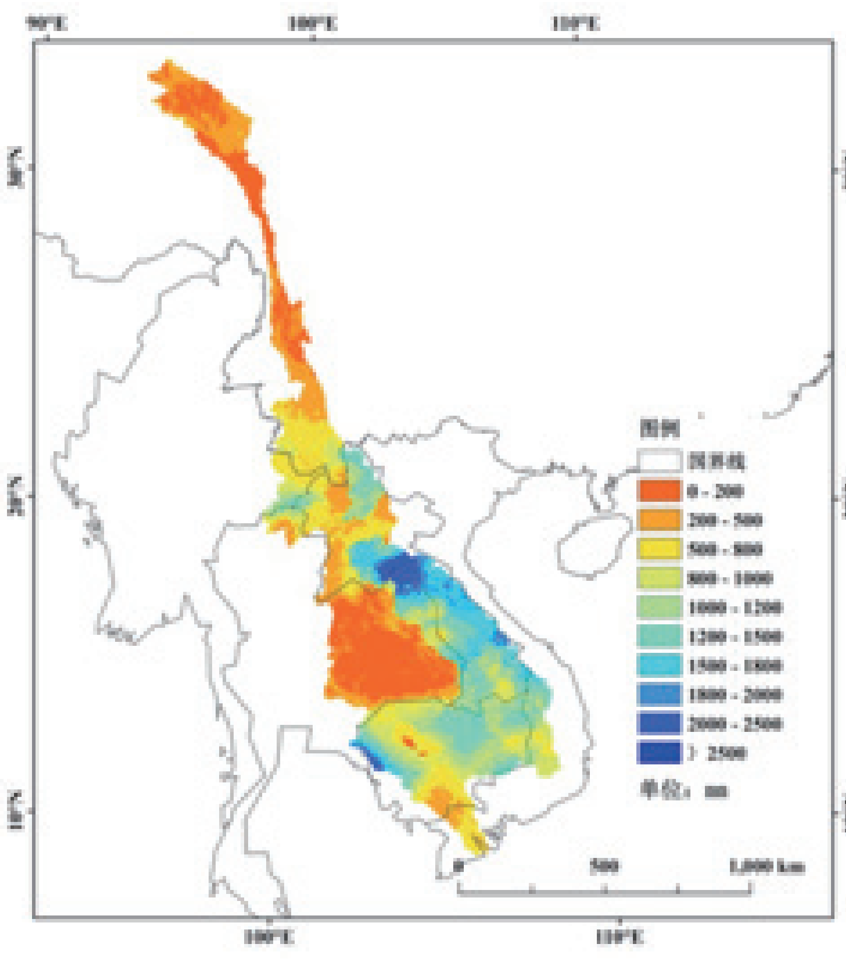

Figure 2 Spatial distribution map of annual precipitation in Lancang-Mekong River Basin

2.3 Hydrological characteristics

The Lancang River Basin occupies with an area of 164,400 km^2, equivalent to 20.7% of the Lancang-Mekong River Basin. The Lancang River accounts for about half (57%) of the Lancang-Mekong River (4,884 km) in length. However, the average annual runoff, registering about 64 billion m^3, only represents 13.5% of the level of the entire basin (475 billion m^3). The utilization rate of water resources is less than 1% of the level of the entire basin. Surface runoff mainly comes from rainfall, melting snow, and groundwater, which varies greatly between the rainy and dry seasons. In the dry season from November to next April, water resource utilization mainly relies on melting snow and groundwater. The water resources occupied by the riparian countries are as shown in the table below.

Table 1 Water resources occupied by riparian countries

Country	Basin area /10,000 km^2	Percentage of total basin area/%	Multi-year average water resources/100 million m^3	Percentage of total water resources of the basin/%	Territory area /10,000 km^2	Ratio of basin area to territory area/%
China	16.5	21	760	16	960	1.72
Myanmar	2.4	3	94.6	2	67.7	3.60
Laos	20.2	25	1661.9	35	23.7	85.23
Thailand	18.4	23	807.3	18	51.3	35.87
Cambodia	15.5	20	901.9	18	18.1	89.34
Vietnam	6.5	8	523.5	11	33.0	19.70
Total	79.5	100	4749.2	100	——	——

2.4 Typical flood and drought disasters

Due to special geographical and hydrological conditions, the Lancang-Mekong River Basin is prone to flood and drought disasters because of extremely uneven spatial and temporal distribution of precipitation coupled with disparity of water conservancy infrastructure such as reservoirs and dams in the riparian countries. This poses a great threat to the production and life, and even survival of people living in the region. Floods and droughts are currently the major water problems facing the Lancang-Mekong River Basin.

2.4.1 Flood events in typical years

In September 1996, the highest daily average water level exceeded the safe water level at five hydrological stations, namely Nong Khai, Mudahan, Pakse, Stung Treng, and Kratie, and the peak flow at Stung Treng station reached 69,800 m^3/s. This formed a regional major flood seen once in 10–20 years in the lower Mekong River.

In August 2008, a flood seen once in 20–50 years hit parts of Laos, Thailand, and Cambodia, mainly in the section of Luang Prabang and from Vientiane to Nong Khai.

At the end of September 2011, a large flood broke out in the Mekong River Basin, drowning the downstream areas for several weeks. Parts of Cambodia, Vietnam, and Thailand were severely affected with about 1,000 people killed. The World Bank estimated that Thailand's economic losses caused by the flood approximately totaled 45 billion US dollars, about 70% of which occurred in manufacturing.

2.4.2 Drought events in typical years

The 2004 drought exerted a very serious impact on Vietnam, Cambodia and Thailand, and caused a total loss of about 4,200 US dollars in the Mekong Delta. In Cambodia, the severest drought recorded in recent years left 500,000 people in food shortage. In Thailand, such serious drought affected 63 of the 76 provinces and about 9 million people across the country.

In early 2016, the Mekong River Basin suffered severe drought. In Vietnam, the worst drought recorded in 90 years affected 39 of the 63 provinces, and made agriculture and aquaculture lose about 5.2 trillion rupiah (about 230 million US dollars), representing 2.3% of the gross domestic product (GDP) of the region.

2.5 Status and needs of water resource development and utilization in riparian countries

Due to differences in economic development and geographical environment, the riparian countries are divided in the level and pattern of development and utilization of Lancang-Mekong water resources.

2.5.1 Status of water resource development and utilization

1. China

The Lancang River flows through a deeply-cut canyon with steep riverbed, presenting extremely inconvenient transportation. While natural resources are scarce, hydropower resources are abundant, with the availability of 27.37 million kW arising from the drop of up to 5,060 m. Hydropower and shipping represent the main ways of water resource development and utilization in China. In terms of hydropower, there are currently eight large hydropower stations planned and constructed in the mainstream (as shown in the figure below). Nevertheless, the actual degree of development is relatively low. The average hydropower resource utilization rate (defined as the ratio of water supply outside the river to the average annual water resources) is only 8.7%.

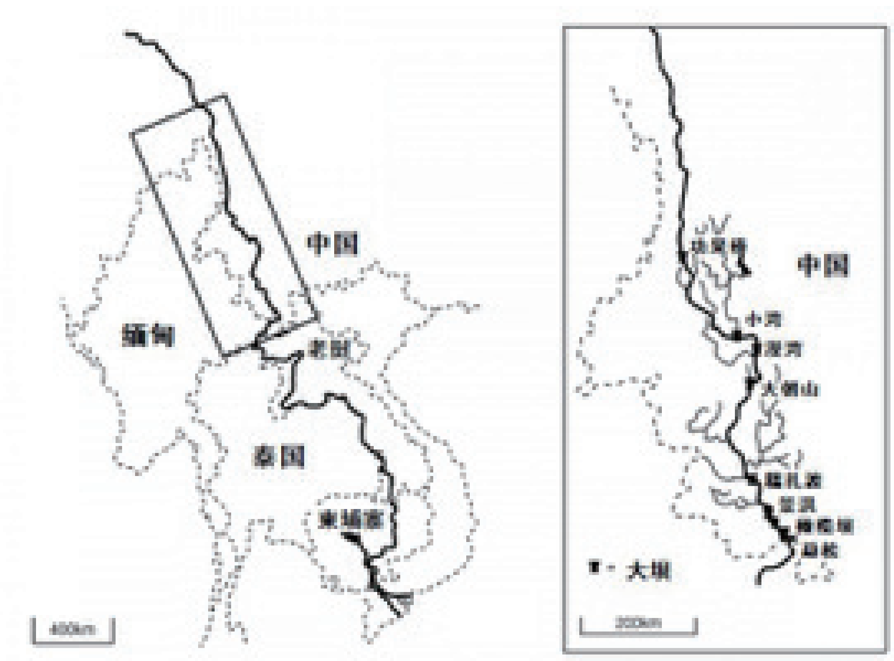

Figure 3 Distribution map of cascade hydropower station on the Lancang River

2. Myanmar

Myanmar has a very limited amount of exploitable water resources of the Mekong River as it accounts for only 3% of the basin area and 2% of the river runoff. Myanmar mainly takes water resources for shipping and hydropower development. In recent years, it has actively promoted international cooperation and accelerated hydropower development, though there are only a few small-scale agricultural irrigation projects.

3. Laos

Laos embraces most of the Mekong hydropower resources, with 97% of the territory located in the basin. It possesses very rich hydropower reserves and focuses on hydropower development in the utilization of Mekong water resources. However, the utilization rate is not high as only 4% of the hydropower reserves have been exploited. The earliest built hydropower station, called Nam Ngum 1 Dam, has an installed capacity of 155 MW, and supplies power mainly to Thailand. Two hydropower stations are under construction in the mainstream of the Mekong River, namely Xayaburi and Don Sahong, and are expected to be completed by the end of 2019. Agriculture accounts for 84.7% of the total water use in Laos. Despite sufficient surface water resources, of more than 700,000 hectares of cultivated land in the country, about 150,000 can be irrigated to the maximum in the flood season, and only 4% in the dry season, due to few agricultural irrigation projects.

4. Thailand

In Thailand, the Mekong River mainly drains the Khorat Plateau and splits into the Mun River and Chi River. The country takes water resources from the river for hydropower and irrigation. Hydropower stations have a total installed capacity of more than 200,000 kW, of which the largest is the Nanpeng River Project with an installed capacity of 40,000 kW. As shown in the figure below, many dam projects have been built in the Thailand section of the Mekong River, mainly for irrigation purpose. The existing irrigation area amounts to about 500,000 hectares, but the actual irrigation rate of cultivated land is less than 6%. In order to solve the problem of agricultural irrigation in the northeast region, Thailand launched the Khong-Loei-Chi-Mun water transfer plan, which aims to build 13 dams in 42 years for irrigation projects. The plan will expand the irrigation area by nearly 50,000 km^2 by realizing an annual water transfer of four billion m3. However, this plan has received protests in downstream countries Cambodia and Vietnam and even concerns about environmental security in local residents.

5. Cambodia

Cambodia has a small number of water conservancy projects, and exploits tributaries to a larger degree than the mainstream, with a total installed capacity of 200,000 kW in hydropower stations. Tributary hydropower development projects included in the MRC development plan are expected to realize an effective storage capacity of 13.6 billion m^3, a combined installed capacity of 920,000 kW, and an irrigation area of 580,000 hectares.

6. Vietnam

In Vietnam, the Mekong River is rich in hydropower resources. The average annual runoff registers 475 billion m^3, making the river navigable to 3000-ton ships. The theoretical hydropower reserves reach 9.25 million kW, and currently, the annual power generation stands at 3.423 billion kWh, the total installed capacity, about 1.2 million kW, and the effective storage capacity, 3.8 billion m^3. Hydropower stations are mainly located in the basin of Sekong River, Sesan River, Sre Pok River. As shown in the figure below, hydropower and irrigation dominate the utilization of water resources.

Stable water flow and gentle terrain form favorable conditions for water resource development and utilization. The drainage area in Vietnam covers 65,000 km^2, accounting for about 8% of the Mekong River Basin and 18% of Vietnam's territory area. On the one hand, the utilization rate is low due to lack of funds. On the other hand, water availability is limited as a large amount of freshwater resources are consumed by serious seawater intrusion. Hence, Vietnam mainly takes the Mekong water resources for agricultural irrigation. Nevertheless, only 50*100,000 hectares of about 2.4 million hectares existing cultivated land can be irrigated.

Obviously, water resources of the Lancang-Mekong River are largely used for shipping, hydropower development, agricultural irrigation, and fishery. These different ways of utilization have different impacts. For example, shipping falls into the category of non-consumable water utilization. Hydropower development has changed the spatial and temporal distribution and hydrodynamic characteristics of water resources. Agriculture consumes the most water resources, followed by fishery. The specific hydropower projects, irrigation projects and irrigated area of the four MRC countries are as shown in the tables below.

Table 2 Statistics of hydropower projects in four MRC countries

Country	Mainstream		Tributaries		
	Under construction	Planned	Constructed	Under construction	Planned
Cambodia		2	1		11
Laos	2	7	11	9	71
Thailand			7		
Vietnam			7	5	3
Total	2	9	26	14	85

Table 3 Statistics of irrigation projects and irrigation area of the four MRC countries

Country	Number of projects	Total irrigation area /10,000 hectares	2030		2060	
			Irrigation area /10,000 hectares	Increase rate/%	Irrigation area /10,000 hectares	Increase rate/%
Cambodia	2091	50.4	77.2	53	83.8	66
Laos	2333	16.6	21.3	28	21.5	29
Thailand	6388	141.2	141.2	0	141.2	0
Vietnam	608	192	192	0	192	0

2.5.2 Analysis of water resource demand

Due to the different economic development patterns and levels, the demand for water resources development and utilization varies widely among countries in the Lancang-Mekong River Basin. China makes use of the mainstream of the Lancang River for shipping and hydropower, and takes water from tributaries for irrigation and industrial use. As one of the least developed countries in the world, Laos attaches great importance to the development and utilization of hydropower resources. In order to get rid of poverty, the Lao government plans to vigorously develop hydropower and build multiple hydropower stations on the mainstream and tributaries of the Mekong River to meet the needs of modernization and industrialization. Agriculture and fishery are also key sectors of development in the future. Agriculture accounts for 26.7% of the GDP and 10.11% of the land area in the country, and about 60,000 hectares of agricultural land need to be irrigated by the Mekong River. In Thailand, the Mekong River is very important for farmland irrigation. The annual water consumption of agriculture (including fisheries) reaches about 9.352 billion m^3, second only to the level of Vietnam. Though most economically developed among the five countries in the Greater Mekong Subregion, Thailand has a large hydropower demand because the lack of electricity has restricted the economic progress. Cambodia has been once reduced to poverty following the civil war and conflict. With huge hydropower resources to be developed, the government has included hydropower in the priority development projects. The six hydropower projects funded by China were completed and put into operation around 2015, forming an average annual output of 3.998 billion kWh. Vietnam's water demand for the Mekong River is mainly embodied in ecological security and agricultural irrigation. Water replenishment to the Mekong River is crucial to the agricultural production and economic development of the region. Since the Mekong River forms the border of short length between Laos and Myanmar, the Mekong water resources are less available in Myanmar. According to the data published by the Food and Agriculture Organization (FAO) of United Nations, the overall demand for and dependence on external water resources of the Lancang-Mekong River are very different among the riparian countries, as shown in Table 5.

Table 4 Overview of water resources development, utilization and demand of Lancang-Mekong countries

Country	Conditions for development	Overview of development and utilization	Water resource demand
China	Very good	Abundant hydropower resources, focus on hydropower and shipping, low overall level of development, sound use for shipping, and few use for irrigation	Mainstream used for hydropower development and shipping, and tributaries for irrigation and industry, and small irrigation and domestic water use
Myanmar	Poor	Very small amount of exploitable hydropower resources, focus on shipping and hydropower, low level of hydropower development, and low utilization rate for irrigation	Certain needs of shipping and hydropower development
Laos	Good	Rich hydropower resources, focus on hydropower development, but low utilization rate of hydropower resources, low utilization rate for agricultural irrigation	Large water demand of hydropower and shipping, and large water demand of agriculture and fishery
Thailand	Moderate	Rich hydropower resources, focus on hydropower and irrigation, cross-basin water transfer plan, moderate overall level of development	High water demand of aquaculture and agricultural irrigation, and low water demand of hydropower development
Cambodia	Moderate	Focus on hydropower, agricultural and fishery development, low utilization rate for hydropower and irrigation, and high level of fishery development	High water storage needs of Tonle Sap Lake
Vietnam	Very good	Rich hydropower resources, high level of hydropower development and shipping development, low utilization rate for irrigation	Large water demand of ecological and agricultural irrigation

Table 5 Water resource occupancy and dependence of Lancang-Mekong countries

Country	Total domestic sustainable water resources (km^3)	Total external inflow of sustainable water resources (km^3)	Dependence on external water resources (%)
China	2840	27.32	0.96
Myanmar	1168	165	14.13
Laos	33.5	143.1	42.91
Thailand	438.6	214.1	48.81
Cambodia	476.1	355.5	74.67
Vietnam	884.1	524.7	59.35

2.6 Relevant regional organizations on water resources

The riparian countries of the Lancang-Mekong River, namely China, Myanmar, Laos, Thailand, Cambodia, and Vietnam, have different political systems and cultural and religious philosophies, as well as water resources management systems, laws and regulations. The existing regional organizations related to water resources in the basin are described below.

2.6.1 MRC

The MRC was built on the Committee for Coordination of Investigations on the Lower Mekong Basin that was initiated by the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) in 1957. It was formally established in April 1995 as Cambodia, Laos, Thailand and Vietnam signed the Agreement on Cooperation for Sustainable Development of the Mekong River Basin in Chiang Rai, Thailand, to cooperate on such priority areas as comprehensive development and utilization, water resources protection, disaster prevention and mitigation, and shipping safety of the river basin. In 1996, China and Myanmar became dialogue partners of the MRC.

China attaches great importance to its relations with the MRC. Since 1996, the two sides have held 22 consecutive dialogues. In order to help the riparian countries to prevent and mitigate disasters, China has provided for free the MRC with flood-season hydrological data of the Lancang River for 15 consecutive years since 2003.

2.6.2 LMC mechanism

In November 2014, Chinese Premier Li Keqiang proposed to establish the LMC framework at the 17th China-ASEAN Summit. In March 2016, the First LMC Leaders' Meeting was held in Sanya, Hainan to fully launch the LMC mechanism. In January 2018, the Second LMC Leaders' Meeting took place in Phnom Penh, Cambodia, marking a transition of the LMC mechanism from the cultivation period to the growth period.

The LMC member states include China, Cambodia, Laos, Myanmar, Thailand, and Vietnam. The LMC mechanism aims to deepen the good-neighborly friendship and pragmatic cooperation and bolster the economic and social development of the six riparian countries, with a view to an economic development belt and a community of shared future. While enhancing the well-being of their peoples, it will support the ASEAN Community construction and regional integration, and promote the South-South cooperation and the implementation of the 2030 Agenda for Sustainable Development.

Driven by the LMC Mechanism, the Joint Working Group for Lancang-Mekong Water Resources and the Lancang-Mekong Water Resources Cooperation Center have been set up one after another, laying a sound foundation for advancing water resource cooperation, high-level mutual visits, technical exchanges, and personnel training among countries in the region.

Chapter 3 Statistical analysis of Lancang-Mekong water resource data

This chapter applies appropriate statistical analysis methods to examine the changes and correlations of precipitation, water level, water flow, and water quality in the Lancang-Mekong River Basin. The data used include the daily precipitation data and water level data from 22 stations in the Lancang-Mekong River Basin between 2009 and 2018, monthly water flow data from eight stations between 2006 and 2016, and water quality data for 2011 and between 2013 and 2017 (some data are missing for each station in each year).

3.1 Methods

Linear trend estimation, Mann-Kendall trend analysis, and Karl Pearson coefficient of correlation are combined to analyze the data.

3.2 Data collection

Through data source identification and statistical analysis, water resource data for nearly ten years are collected from the MRC and relevant organizations, water resource bulletins and databases of the competent departments of riparian countries, and research reports of global authoritative agencies, and then identified for analysis. The primary data source is the reports downloaded from the MRC's official website (http://www.mrcmekong.org).

3.3 Trend and correlation analysis

Historical changes in the hydrology and water environment of the river basin and the correlations between water resource elements are investigated using the above-mentioned methods. The results are as follows:

3.3.1 Trend analysis

1. Precipitation

Rainfall is unevenly distributed in the Lancang-Mekong River Basin during the year, largely concentrated in the flood season. Even in the flood season, there is uneven spatial and temporal distribution of precipitation in the basin. Upstream areas have significantly higher annual average precipitation than downstream areas. The middle and upper reaches see more rainfall in July than October, while the lower reaches experience concentrated rainfall in October. Between 2009 and 2016, the average annual precipitation in the flood season exhibited an upward trend at the upstream stations, but downward trend at the downstream stations. Among all the 22 stations, only five have passed the M-K test because the data length is too short to meet the 30-year requirement and some data are missing. The test results are for reference only.

2. Water level

From the temporal point of view, the water level reached the peak in 2011 at eight major stations in the Lancang-Mekong River Basin. While 2011 was a typical rainy year with more floods, 2015 was a dry year with extremely low water level at each station. China began to make emergency water replenishment to the Lancang-Mekong River in 2015, and gradually restore the 2009 water level at the eight stations in 2018. Compared with upstream stations, the peak water level came far late at the downstream stations in the flood season. The average annual water level varied little between the flood season and non-flood season at both the upstream and downstream stations, but widely at the midstream stations. The R-squared (r^2) value of water level is close to 0 at each station in the basin, indicating that the water level at each station does not change significantly over time in the flood season. The M-K test results are not ideal, and no test value exceeds 1.28. The test results are for reference only because the data length is not less than 30 years.

3. Water flow

Between 2006 and 2016, the average annual water flow at each station exhibited a downward trend. Among the eight major stations, only two upstream stations have a slightly larger r2 value, indicating an obvious decline in the upstream flow of the Mekong River. However, the r2 values of the other stations are close to 0, indicating that water flow changes at these stations were not obvious over time.

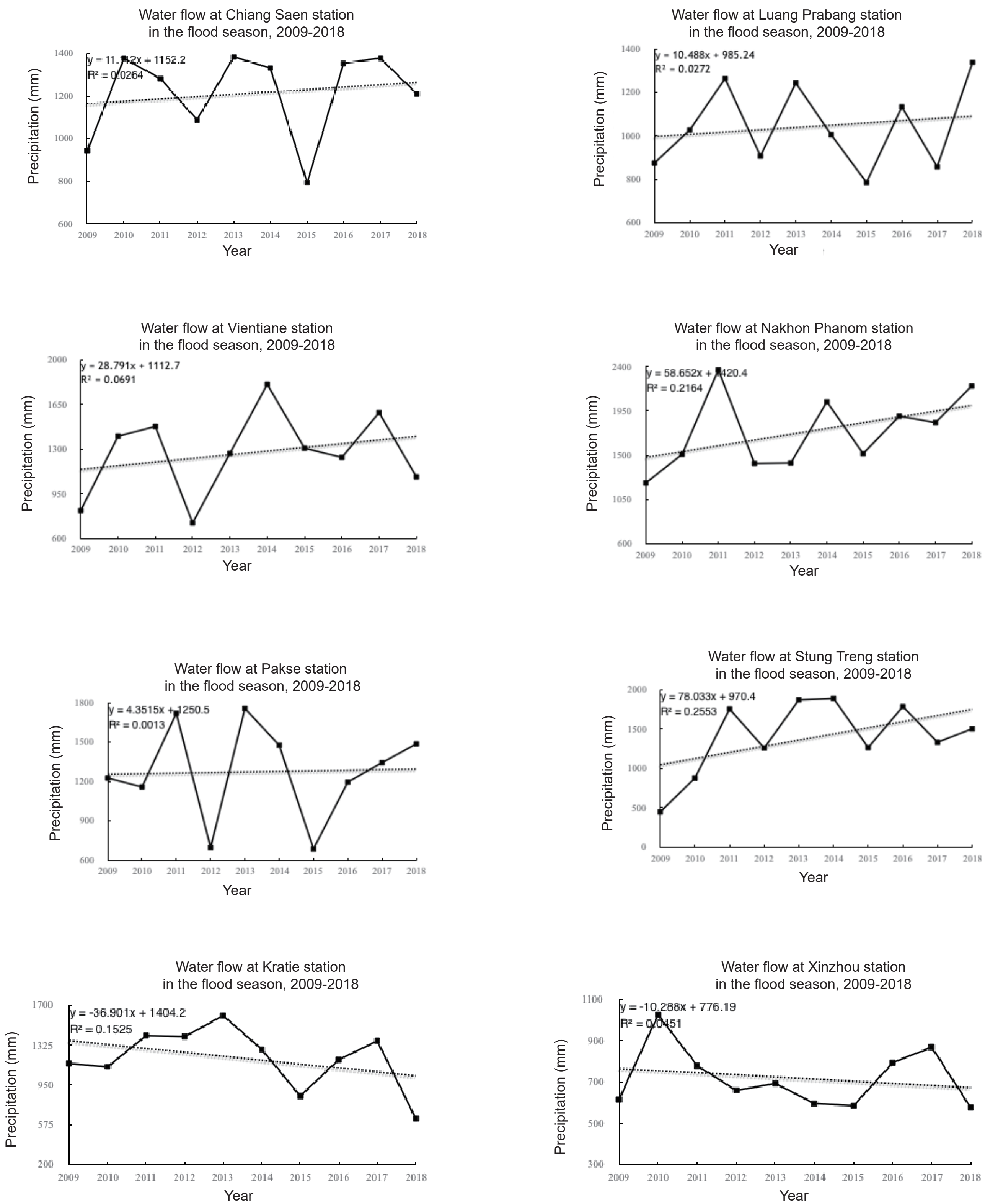

Figure 4 Linear fitting results for precipitation in the flood season at major stations of the Mekong River

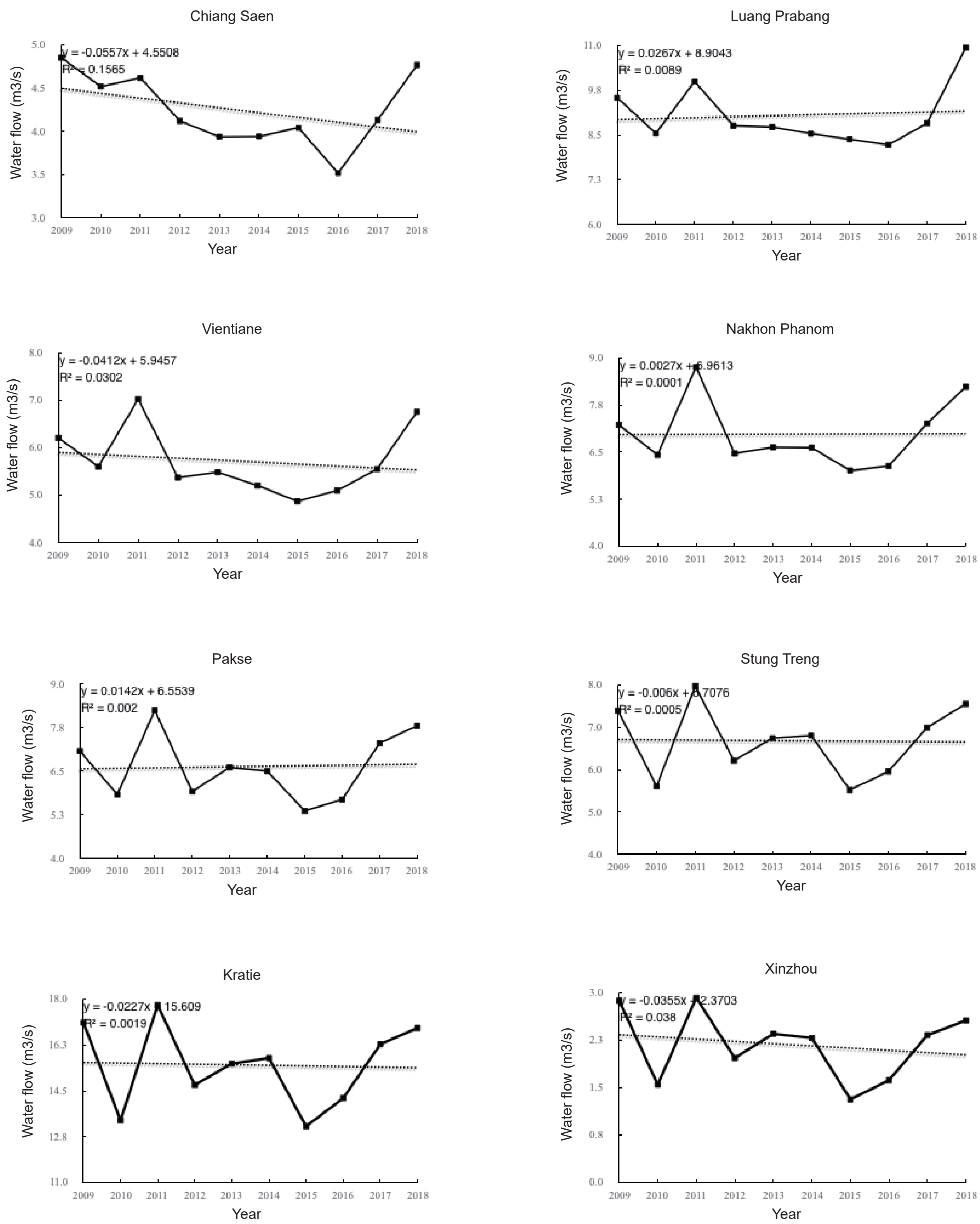

Figure 5 Linear fitting results for water level in the flood season at major stations of the Mekong River, 2009–2018

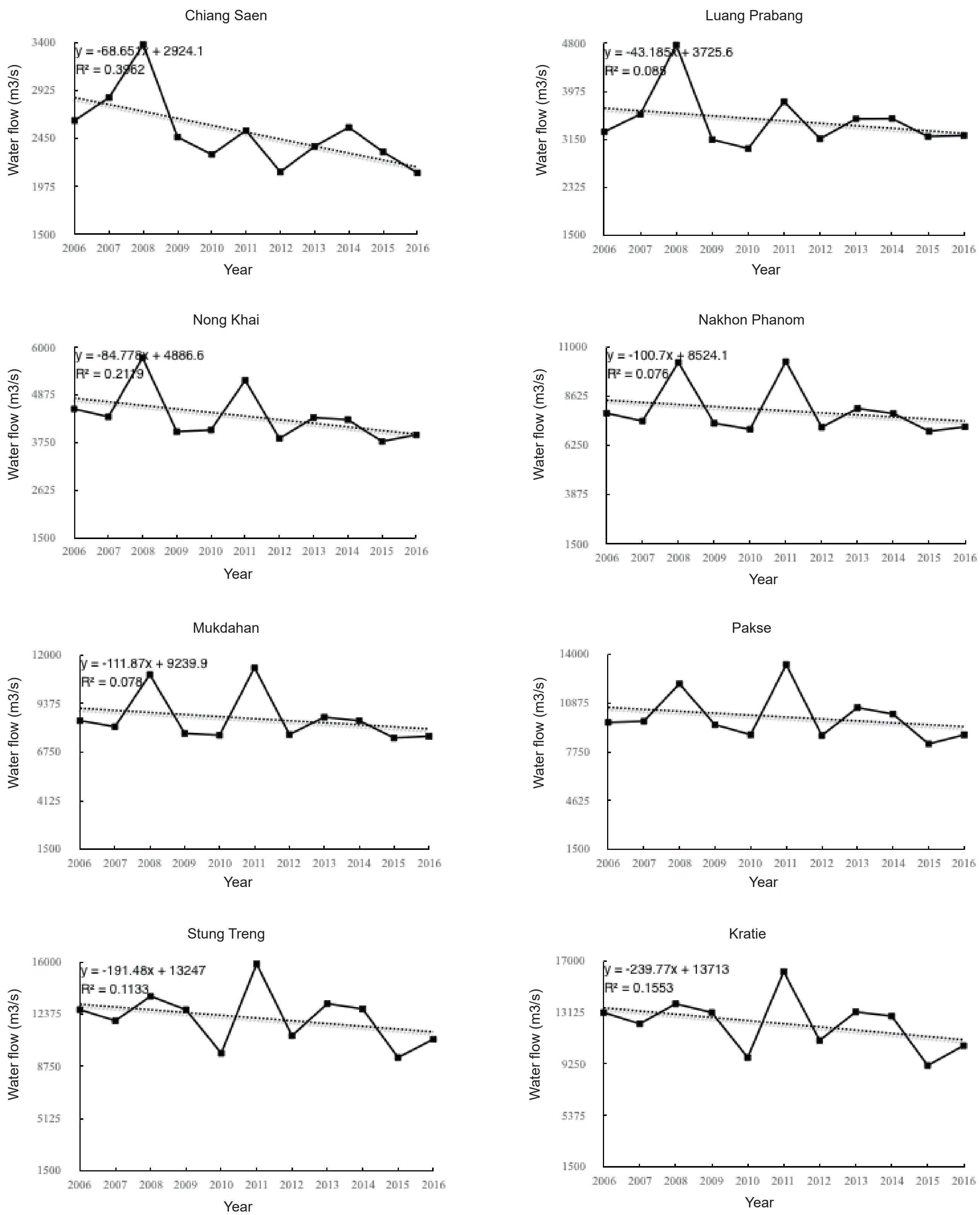

Figure 6 Linear fitting results for water flow in the flood season at major stations of the Mekong River, 2009–2018

4. Water quality

In 1985, the riparian countries began measuring water quality indicators, such as pH, total suspended solids (TSS), and electrical conductivity (EC), at 22 stations on the mainstream and tributaries to evaluate the water quality of the Lancang-Mekong River. The temporal and spatial variance of each water quality indicator is hereby analyzed.

(1) pH

The median pH value of the Mekong River showed a downward trend between 1985 and 2014 and slightly rose after 2014, but it stayed within the range (6–9) of the MRC Technical Guidelines for Protection of Human Health and Technical Guidelines for Protection of Aquatic Life.

According to the MRC's Water Quality Monitoring Report, the overall decline in pH value may reflect more impact on the Mekong River brought by accelerating industrial development and urbanization in the lower Mekong region.

(2) TSS

The TSS content fell sharply between 1985 and 1991, with the average value down from about 300 mg/L to about 80 mg/L, and climbed to 103.1 mg/L in 2017. According to the MRC's Water Quality Monitoring Report, the TSS concentration varies greatly during the year, significantly higher in the rainy season than the dry season (from November to next April).

(3) EC

Between 2000 and 2017, the median EC value of the Mekong River tended to be stable with slight increase. According to the the MRC's Water Quality Monitoring Reports 2015–2017, the EC level was high in the upstream and downstream sites, and relatively low in the midstream sites.

(4) Nitrate nitrogen (NO_{3-2}-N)

Between 2000 and 2017, the media NO_{3-2}-N content in the Mekong River tends to rise by small magnitude, from 0.218 mg/L in 2000 to 0.315 mg/L in 2017. As water flows from upstream to downstream, the NO_{3-2}-N concentration in each station presented u-shaped distribution. It reached the highest in the delta, indicating that polluted wastewater containing nitrate and nitrite may increase, probably due to intensive agricultural activities and urbanization.

(5) Ammonia nitrogen (NH_4-N)

Between 1985 and 2017, the median NH_4-N content in the Mekong River showed an upward trend as a whole with large fluctuations. It ascended from 0.02 mg/L in 1985 to 0.036 mg/L in 2017.

(6) Total phosphorus (TOT-P)

The median TOT-P content in the Mekong River dropped slightly between 1985 and 2002, rebounded rapidly after 2002. The median value stood at 0.063 mg/L, 0.041 mg/L, and 0.079mg/L in 1985, 2002 and 2017 respectively.

(7) Dissolved oxygen (DO)

The median DO content in the Mekong River did not change much between 1985 and 2017, staying around 7.0 mg/L.

(8) Chemical oxygen demand (COD)

The median COD value in the Mekong River did not change much between 1985 and 1990, but increased amid large fluctuations after 1990. The level rose and fell around 1.6 mg/L between 1985 and 2003, and 2.0 mg/L between 2004 and 2017.

3.3.2 Correlation analysis

Considering data length and completeness, the monthly data of precipitation, water level, and water flow for the 2009–2016 flood season (June-October) are selected for correlation analysis. In addition, the monthly data from November 2015 to May 2016 are also used on account of China's emergency water replenishment to the Mekong River.

1. Precipitation and runoff

At most stations of the Mekong River, precipitation reaches the maximum in June, while runoff peaks in August, leading a rainy season from May to October, and the flood season from June to November. Therefore, the correlation between precipitation and the next month's runoff is analyzed. It is found that the coefficients of correlation are significantly positive in most of the the stations and time periods, suggesting there is an indeed lag in the response of runoff to precipitation. In some time periods, however, the correlation at certain stations is not obvious or even negative. This is because the specific lag time is uncertain, and constrained by data sources, the precipitation data cannot accurately represent the precipitation of the overall basin.

2. Precipitation and water level

Similarly, significantly positive correlation was observed between precipitation and the next month's water level in more stations and time periods, indicating an indeed lag in the response of water level to precipitation. There is no obvious or even negative correlation in some stations or time periods because the specific lag time is uncertain, and constrained by data sources, the precipitation data cannot accurately represent the precipitation of the overall basin.

3. Water flow and water level

Water flow and water level are highly correlated during all time periods at various stations, except weak correlation during some periods at the Kratie Station.

Chapter 4 Forecasting and analysis of future trends of water resources in the Lancang-Mekong River Basin

Based on the analysis of historical data of water resources and water environment, we have gained a basic understanding of the current hydrological situation, water resources and water environment of the Lancang-Mekong River Basin. However, due to the impact of climate change and human activities, the situation of water resources and water environment will keep evolving in the future. Therefore, there is an imperative need to forecast and analyze the future hydrology and water environment of the river basin. Through literature review covering papers from SCI journals and reports of authoritative institutions, the study draws conclusions on the future trends of hydrology and water environment in the Lancang-Mekong River Basin, which are recognized to a large extent by academics and government agencies.

Based on research and prediction of changes in hydrological and meteorological elements and water quality, the following conclusions are made: The spatial and temporal distribution of precipitation in the basin will become more uneven; The average annual runoff in the basin will not show an obvious trend and will exhibit small inter-annual variation; In the future, the changes in precipitation and runoff in the basin will vary in different areas and stations; The average precipitation in the basin will be on the rise. As climate change has accelerated the water cycle, water resources in the basin will become more concentrated in the rainy season, which is likely to cause extreme flood disasters.

The construction of water conservancy projects in the Lancang-Mekong Basin will exert a significant impact on the annual distribution of downstream runoff. The average water flow will decline in the flood season and grow in the non-flood season, but the impact of reservoirs will gradually weaken along the downstream.

In the future, the risk of droughts will be escalated in the Lancang-Mekong River Basin due to considerable increase in the intensity and peak of droughts. Under the impact of climate change, flooding intensity and frequency in the upper reaches will grow at an increasing magnitude. The characteristics of floods in the lower reaches are dominated by climate change, and the possibility of extreme floods will become larger in the future.

According to the 2018 Environmental Status Bulletin of Yunnan Province, most of the control sections of the Lancang River met the Class III or higher standards, demonstrating overall good water quality. According to the MRC's water quality monitoring reports 2011–2017 covering all built 22 stations, most sections of the Mekong River had good water quality. However, with the intensification of human activities such as urbanization, mining, and pesticide application, coupled with inadequate management, the water quality of the Lancang-Mekong River has been deteriorating.

Chapter 5 Analysis of water resource management policy and technical cooperation capacity building in the Lancang-Mekong River Basin

Water resources are among the most important exploitable resources in the countries along the Lancang-Mekong River. For riparian countries at the stage of rapid economic and social development, many water resource problems need to be addressed amid the growing demand for water resource development and utilization. The riparian countries attach great importance to the development and protection of water resources, but their needs vary due to differences in development stage and geographical location. This complicates the relationship in the development and utilization of water resources, the protection of aquatic environment, and the prevention of flood and drought disasters across the borders. A high degree of mutual trust and pragmatic cooperation is required to effectively coordinate and promote cross-border cooperation in the development, utilization, and protection of regional water resources.

5.1 Past mechanisms for water resource management are deficient in supporting cooperation in water resources. As cooperation had limited effectiveness, conflicts in water resource development between the riparian countries become increasingly prominent.

For a long time (before 2016), the cooperation mechanisms in the Lancang-Mekong region could not effectively harmonize the differences in the development and utilization of water resources between various countries. The riparian countries lacked leadership and were subject to external countries and organizations in terms of cooperation model, project content, fund, and technology. Meanwhile, there was no cooperation mechanism that is jointly participated and established by the riparian countries and meets the actual development needs of each country. Overall, the water resource management of the Lancang-Mekong River is imperfect in the following aspects:

First, the cooperation mechanisms are largely dominated by countries outside the region, and have prominent conflict of interest.

Past cooperation mechanisms in the Lancang-Mekong region are led by countries or organizations outside the region and have outstanding conflict of interest, except for a few such as the Greater Mekong Subregion (GMS) Economic Cooperation and ASEAN-Mekong Basin Development Cooperation (AMBDC).

On the one hand, there are conflicts of interest between actors outside the region. These external stakeholders with different interests in the region often play games to ensure their own interests while compromising the overall cooperation effects. International organizations pay attention to lending, human resource development, and cross-border infrastructure projects. Non-government organizations (NGOs) are keen on environmental protection and civil society. Western developed countries actively promote their own basin governance models to enhance their political, technological and cultural soft power and expand national influence. The different interests and concerns of stakeholders lead to competition and lack of trust among various cooperation mechanisms, which undermines the actual cooperation effects.

On the other hand, there is a contradiction between environmental supremacy in Western developed countries and socio-economic development needs of the Lancang-Mekong region. The cooperation mechanisms led by external countries more reflect the ideas and intentions of the initiators, and easily overlook and weaken the actual needs of local partners. Those supported by foreign funds and technologies are also affected and restricted in terms of focus areas, cooperation models, and project content. Without the leadership of riparian countries, such cooperation mechanisms are not well adapted to the Lancang-Mekong region.

Second, water resource cooperation covered by past cooperation mechanisms is not authoritative and effective enough in the absence of upstream countries.

The overall utilization and protection of water resources of the Lancang-Mekong River as a whole requires the participation of all stakeholders in the basin. Prior to 2016, there were no water resource cooperation mechanisms jointly established or participated by the six riparian countries, especially the participation of upstream countries (China and Myanmar). As a result, the various aquatic environment security policies and measures, adopted so far to protect the water quality and rare fish species of the Mekong River, are limited to decentralized management that addresses local problems, instead of comprehensive management. A systematic framework for cooperative development and comprehensive governance of the entire basin has not formed. For example, the GMS and the MRC had a relatively high level of cooperation at the time. However, the GMS focuses on economy and connectivity, with little attention paid and result produced in the field of water resources. The MRC highlights cooperation in water resources, especially cooperation in the development, utilization, and protection of cross-border water resources, but it does not include China and Myanmar as member states, but only as dialogue partners with limited participation. This impairs the regional recognition, authority, and effectiveness of the MRC mechanism.

Third, past cooperation mechanisms mostly focus on the economic field, and are not effective in the field of water resources.

Past cooperation mechanisms in the Lancang-Mekong region place emphasis on economic, trade and transportation cooperation, and present level-level cooperation in cross-regional public health and environmental protection. In order to avoid unnecessary troubles and conflicts, they are generally not involved in the field of water resources, especially cross-border water resources, because of diverse stakeholders and complex divergences. For example, the Lower Mekong Initiative led by the United States devotes energy to democratic transformation and some functional cooperation in the environment and climate. While the ASEAN-Japan Comprehensive Economic Partnership led by Japan provides government development assistance in the economic field, the Korea-Mekong Foreign Ministers Meeting led by South Korea emphasize infrastructure, green growth, agriculture and rural development, and personnel training. The Indian-Mekong cooperation focuses on tourism, education, culture, transportation and other fields. The Plan for ASEAN Mekong Basin Development Cooperation and the Initiative for ASEAN Integration lean toward transportation and energy fields.

The MRC is the earliest water resource cooperation mechanism founded in the region that focuses on the development and utilization of water resources in the Mekong River Basin. However, the following problems prevent it from playing the role of resolving water conflicts and contradictions: i) As a regional intergovernmental international organization, the MRC has no binding force and enforcement power on member countries; ii) The failure to include all riparian countries limits its actual effectiveness; and iii) Cooperation in water resources is divorced from cooperation in other fields such as politics, economy, and security.

5.2 The LMC mechanism, as an effective supplement to regional cooperation in water resource development, promotes cooperation, consultation, and sharing among the riparian countries.

Being in the stage of rapid economic and social development, countries in the Lancang-Mekong region all have urgent demands for resources and energy. In the future, they will face more differences and contradictions while bolstering cooperation in the fields of transboundary water resource development and utilization, agricultural irrigation, shipping construction, hydropower development, and environmental protection. However, the regional cooperation mechanisms led by Western countries and international organizations have not been effective enough in coordinating and resolving water resource disputes. This make it very necessary to set up a cross-border water resource cooperation mechanism that is really engaged and led by the riparian countries, has certain binding force, and meets the actual needs of the riparian countries.

In view of the practical necessity of regional cooperation and the imperfection of existing cooperation mechanisms, China proposed in 2016 the establishment of the LMC mechanism that includes all six riparian countries, and suggested water resource management and environmental protection as priority areas of cooperation. Since launched in 2016, the LMC mechanism has made noticeable progress in water resource cooperation, including i) The Joint Working Group for Lancang-Mekong Water Resources and the Lancang-Mekong Water Resources Cooperation Center were set up in Chin; ii) Five-Year Plan of Action on Lancang-Mekong Water Resources Cooperation has been jointly formulated; iii) The Ministerial Meeting of Lancang-Mekong Water Resources Cooperation and the First Lancang-Mekong Water Resources Cooperation Forum were held to strengthen policy dialogue on water resources; iv) Extensive technical exchanges and personnel exchanges have been carried out; v) The sharing of hydrological information and data in the Lancang-Mekong region has been facilitated; and vi) A number of pragmatic cooperation projects that benefit he people of various countries have been jointly prepared and implemented, and achieved remarkable results.

On December 17, 2019, the Ministerial Meeting of Lancang-Mekong Water Resources Cooperation took place in Beijing. Chinese Minister of Water Resources Er Jingping proposed constructive suggestions on future water resource management policies for the Lancang-Mekong River Basin: i) The Lancang-Mekong water resource cooperation should fully respect the rights and interests of riparian countries to rationally develop and utilize water resources; ii) The Lancang-Mekong water resource cooperation should fully consider the major concerns of each other; iii) Only by cooperation can the win-win of the six riparian countries be achieved; and iv) The specific issues in Lancang-Mekong water resource cooperation should be handled by the riparian countries themselves. He highlighted that the LMC mechanism should adhere to the following principles: The Lancang-Mekong River Basin nurtures the six riparian countries. It is the basin of our six riparian countries, not other countries. The strategies for Lancang-Mekong water resource cooperation will and should be led by our six riparian countries only. The matters concerning the cooperation should be negotiated by our six riparian countries. The pathway for development should be chosen by our six riparian countries.

On this basis, three recommendations are hereby put forward for the next step of cooperation: i) Strengthening the construction of cooperation mechanisms to facilitate consultation; ii) Promoting rational development and utilization for joint construction; and iii) Creating a high-level information platform to facilitate sharing.

Chapter 6 Summary and outlook

Based on the collected data about hydrology, water resources and water environment in the past ten years, the study performs a statistical analysis of the changes in the basic hydrology and water environment of the Lancang-Mekong River Basin. Combined with literature review and the data source identification and statistical analysis, the study summarizes the trends in hydrology and water environment of the Lancang-Mekong River Basin in recent decades.

6.1 Conclusions

Based on collected data, linear trend estimation and Manner-Kendall trend analysis are employed to analyze the overall changes in water level, water flow, precipitation, and water quality of Lancang-Mekong River Basin. Then, the Pearson coefficient of correlation is used to analyze the correlation between precipitation and runoff, between precipitation and water level, between water flow and water level in the basin.

The results indicate that there was large inter-annual variance in precipitation between 2009 and 2018. Precipitation was unevenly distributed during the year, mainly concentrated in the flood season (from June to October). Rainfall occurred significantly more in the upper reaches than the lower reaches. It concentrated in July at the midstream and upstream stations, but October at the downstream stations. The water level of the Lancang-Mekong Basin exhibited a downward trend between 2009 and 2015, but rose back to the 2009 level in 2018 after emergency water replenishment. The highest water level of each station appeared mostly in 2011 and the lowest, basically in 2015. Due to the time of confluence, the highest water level came obviously later at the downstream stations, compared with the upstream stations. The overall water flow of the Lancang-Mekong River Basin presented a downward trend between 2006 and 2016, with the lowest observed in 2012 and 2015. The water flow gradually increased from upstream to downstream. It was unevenly distributed throughout the year at various stations, peaking in August. There is an obvious lag between precipitation and runoff and between precipitation and water level, but the specific time of lag is unknown.

Between 2011 and 2017, the water quality of the Lancang-Mekong River deteriorated slightly. The pH value tended to decline, and the median value at each station was generally around 7.5. The TSS content decreased sharply, with a significantly higher level in the rainy season than the almost dry season (November to next April). The median EC value remained relatively stable, with a slightly higher level in upstream stations than the downstream stations. The DO concentration changed little during the period, with higher measured value in the upper and middle reaches. The NH3-N concentration exhibited an upward trend over the years, and with the flow from upstream to downstream, showed u-shaped distribution among the station, reaching the highest in the delta. The TOT-P content also increased over the years and from upstream to downstream, with the lowest at the upstream stations. The COD level kept fluctuating and showed an upward trend. It increased from upstream to downstream, similar with TOT-P and total nitrogen (TOT-N). Each year, the measured values at multiple stations exceeded the 5 mg/L limit stipulated in the MRC Guidelines for Protection of Human Health.

In addition, through literature review, changes in the precipitation, water flow, and water quality of the Lancang-Mekong River over the past few decades were summarized based on papers on the hydrology and water environment of the Mekong River published between 2010 and 2019. Furthermore, the future trends in the precipitation, water flow, and water quality of the basin are forecasted and analyzed under different climate and human activity scenarios.

In general, the water circulation process in the Lancang-Mekong River Basin will speed up. Precipitation will show an upward trend, and more concentrate in the rainy season. Extreme hydrological events (such as floods) will become more unlikely. Affected by human activities, the water level and water flow in the dry season will be on the rise, but there is still an increasing trend in the frequency and magnitude of droughts. The water quality of the Lancang-Mekong River is relatively good at present, but excessive human activities such as mineral mining, sand mining, and deforestation will pose a great threat, leading to the deterioration of water quality in the basin.

On Lancang-Mekong water resource management mechanisms, existing basin organizations like the MRC have contributed to the rational and sustainable development of water resources in the basin to a certain extent. However, with the continuous improvement of development level, the MRC tends to becomes unable to well coordinate and resolve the contradictions of water resource development among the riparian countries and the cooperation relationship between upstream and downstream.

6.2 Limitations and deficiencies

The results on the hydrology and water environment of the Lancang-Mekong River obtained by the report basically conform to the relevant facts and can be recognized by the academic community. Nevertheless, there are still some limitations:

Data length does not match the analysis methods. For example, the Manner-Kendall method requires longer (>30 years) data to well reflect the evolution trend of data sequences and determine the mutation point of data sequences. The available data sequences are short and can only reflect the general trend of changes.

There is a certain contradiction in reviewed literature. Due to differences in data sources, site locations, and data sequences used in different papers, there are certain errors in the analysis, which leads to different research findings. In view of this, on the one hand, authoritative journals (core Chinese journals and Q1 and Q2 journals) are cited in the literature review. On the other hand, the similar or common conclusions of most (80%) journals are taken as the results of literature review. Thus, credibility can be assured to some extent, despite certain errors.

6.3 Prospects

In the future, research can be further improved in the following aspects: First, the data sequences should be extended, thereby reducing the errors in data representation and method usage; Second, modeling and simulation should be integrated when longer data sequences are available in the future. The various parameters in the model can be adjusted to highlight the focus of research and more intuitively reflect the water resources of the Lancang-Mekong River Basin.

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About LMEC: Lancang-Mekong Environmental Cooperation(LMEC), established in 2017 in Beijing, China, aims to boost the capacity of environmental governance of each country and achieve regional sustainable development through the promotion of environmental cooperation among the Lancang-Mekong Countries.