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Past and Future Changes in Climate and Water Resources in the Lancang–Mekong River Basin: Current Understanding and Future Research Directions

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ABSTRACT

The Lancang–Mekong River (LMR) is an important transboundary river that originates from the Qinghai–Tibet Plateau, China and flows through six nations before draining into the South China Sea. Knowledge about the past and future changes in climate and water for this basin is critical in order to support regional sustainable development. This paper presents a comprehensive review of the scientific progress that has been made in understanding the changing climate and water systems, and discusses outstanding challenges and future research opportunities. The existing literature suggests that: ① The warming rate in the Lancang–Mekong River Basin (LMRB) is higher than the mean global warming rate, and it is higher in its upper portion, the Lancang River Basin (LRB), than in its lower portion, the Mekong River Basin (MRB); ② historical precipitation has increased over the LMRB, particularly from 1981 to 2010, as the wet season became wetter in the entire basin, while the dry season became wetter in the LRB but drier in the MRB; ③ in the past, streamflow increased in the LRB but slightly decreased in the MRB, and increases in streamflow are projected for the future in the LMRB; and ④ historical streamflow increased in the dry season but decreased in the wet season from 1960 to 2010, while a slight increase is projected during the wet season. Four research directions are identified as follows: ① investigation of the impacts of dams on river flow and local communities; ② implementation of a novel water–energy–food–ecology (WEFE) nexus; ③ integration of groundwater and human health management with water resource assessment and management; and ④ strengthening of transboundary collaboration in order to address sustainable development goals (SDGs).

1. Introduction

The Lancang–Mekong River (LMR) is an important transboundary river that originates in the Qinghai–Tibet Plateau region, China and drains to the ocean in the Mekong Delta in Vietnam (Fig. S1 in Appendix A). It is the longest river in Southeast Asia, the seventh longest river in Asia, and the twelfth longest river in the world [1]. Over 70 million people rely on the LMR and its tributaries for water supply, food production, instream transport, and many other services the river system provides to support their livelihoods [2]. The Lancang–Mekong River Basin (LMRB) also houses one of the world's most productive fisheries, and the basin is the second richest in terms of aquatic biodiversity after the Amazon River basin [3,4].

The length of the LMR is approximately 4880 km [3,4]. In the upper portion of the basin—the Lancang River Basin (LRB)—the river flows from the Qinghai–Tibet Plateau and runs through China's Qinghai, Yunnan, and the Tibet Autonomous Region, before entering the lower portion of the LMRB—known as the Mekong River Basin (MRB)—at the border between Myanmar and Laos. The Lancang River runs through steep terrains, experiencing an elevation drop of about 4500 m. In the MRB, the river runs through Laos before becoming the border between Laos and Thailand and then re-entering Laos. The river then flows through Cambodia

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and into Vietnam as a complex delta system before finally draining into the South China Sea [3].

The LMRB covers an area of 795 000 km^2 and ranks as the tenth largest river basin in the world in terms of mean annual flow volume [3]. The basin area is shared among China (21%), Myanmar (3%), Laos (25%), Thailand (23%), Cambodia (20%), and Vietnam (8%). The climate of the LMRB is strongly influenced by the Indian summer monsoon, the East Asian monsoon, tropical cyclones, and the El Niño–Southern Oscillation (ENSO) [4–6]. Annual mean precipitation within the LMRB increases from northwest to southeast [6]. Long-term (1981–2010) mean values of the basin-averaged annual precipitation for the LMRB range from 464 mm·a^{-1} in the LMR to 4300 mm·a^{-1} in the eastern and southeastern parts of the MRB. The annual mean temperature ranges from –4.8 °C in the LMR to 29.0 °C in the southwest region of the MRB [7].

The mean discharge at the river mouth in the Mekong Delta is about 475 km^3·a^{-1}, which provides relatively high water resources per capita for the LMRB in comparison with other large global river basins [3]. Of the total LMRB water resource, approximately 16% comes from the LRB in China, and the rest derives from the MRB, with 35% from Laos, 18% from Thailand, 18% from Cambodia, 11% from Vietnam, and 2% from Myanmar [3]. Despite rich water resources (about 8000 m^3·a^{-1} per capita), the high temporal and spatial variabilities in runoff create seasonal water shortages or scarcity [4]. The Qinghai–Tibet Plateau, where the LMR originates, is more sensitive to climate change than other global regions [8], and the hydrological system of the LMRB has also undergone significant changes due to the climate change [9]. Furthermore, rapid economic development, growing food demands, and energy needs in riparian countries have led to dramatic land use or land cover changes and alterations of hydrological and ecological systems, particularly due to massive agricultural expansion and hydropower development throughout the LMRB [10]. Many studies have indicated that climate change and human activities have substantially altered the LMR streamflow in both its mainstem and tributaries, leading to more frequent extreme events and a longer dry season [11]. Such changes in the hydrologic regime of the LMRB have consequently resulted in the degradation of natural resources in the region—such as fish, water, and land—upon which millions of people in the MRB nations rely [12].

Given this context, there is an urgent need to better understand the changing climate and water resources in the LMRB in order to support regional transboundary collaborations and synthesize scientific progress and the current status—that is, what we know and what remains unclear. This paper aims to ① synthesize the progress that has been made mostly since the year 2010 in the scientific understanding of the changes in climate and water resources in the LMRB and describe the confidence levels regarding both past and future changes [13]; and ② identify knowledge gaps and opportunities for research that can be used to prioritize future scientific efforts. The information on confidence levels is derived based on the guidance of the Intergovernmental Panel on Climate Change (IPCC) for dealing with uncertainties. More specifically, following the IPCC guidance note on the consistent treatment of uncertainties, three types of consistency of evidence (summary terms: "limited," "medium," or "robust") and three types of degree of agreement (summary terms: "low," "medium," or "high") are used for the evaluation of evidence and agreement among findings from different studies [13]. Based on reviewed literature on climate and water changes, very high confidence is assigned to findings with a high level of agreement and robust evidence. Medium confidence is assigned to findings with either a high level of agreement or robust evidence, and low or very low confidence is assigned to findings with a low level of agreement or limited evidence.

2. Climate of the LMRB: Historical change and future projections

2.1. Past and future warming trends

A list of prior studies focusing on changes in precipitation and temperature over the LMRB and its upper (LRB) and lower (MRB) parts is given in Table S1 in Appendix A. With high confidence, these studies have reported increasing trends in annual mean temperature across the LMRB in the past decades. During 1981–2010, the rate of increase was higher in the LRB (0.6 °C·decade^{-1}) than in the MRB (0.2 °C·decade^{-1}) [14]. The warming trends in both the LRB and MRB exceed the global average temperature rise (0.17 °C·decade^{-1}) since 1981, as reported by Hartfield et al. [15].

No statistically significant changes in annual maximum and minimum temperatures were determined over the LRB between the early 1980s and 2010 [14], but the annual maximum and minimum temperatures showed the same warming trends as the mean annual temperature in the MRB [7]. The seasonal warming trends showed the highest rate for winter (December–February) across both the LRB [14] and the MRB [7] during 1981–2010. However, studies have reported that the LRB was already experiencing warmer winters before 1981, such as during the period from the 1960s to the early 2000s [16].

Statistically significant warming trends (0.02 °C·decade^{-1}) in mean annual temperature are expected (with high confidence) over the LMRB during the 21st century [17,18], with a higher rate in the northern and southern parts [19]. However, these temperature projections vary largely depending on the scenario used in the climate models (Table S1). A warming trend (0.01–0.03 °C·decade^{-1}) is also projected over the MRB [20], while warming over the LRB is projected to be slightly more evident and consistent [17]. The daily maximum temperature over the MRB is expected to increase by 2050, with estimates ranging from 1.6 °C in the northern and southwestern parts to 4.1 °C in the southeastern areas, where there is a historically cooler climate than in the central part of the MRB [20]. Accordingly, more frequent annual hot days (daily maximum temperature > 33 °C) are projected, particularly in the southern part of the MRB [21]. In addition, projections for seasonal temperature changes are fairly homogeneous across the MRB, with a warmer climate projected during wet seasons (1.7–5.3 °C) than during dry seasons (1.5–3.5 °C) for the near future (2020–2050) [20]. Meanwhile, daily mean temperatures across the LRB are projected to be higher during dry seasons (7.5–10.5 °C) than during wet seasons (6.0–7.5 °C) under the 6 °C warming scenario [17]. Moreover, warmer temperatures, which have historically been observed at lower elevations in the MRB, will be experienced at higher elevations, particularly above 400 m, during this century [20].

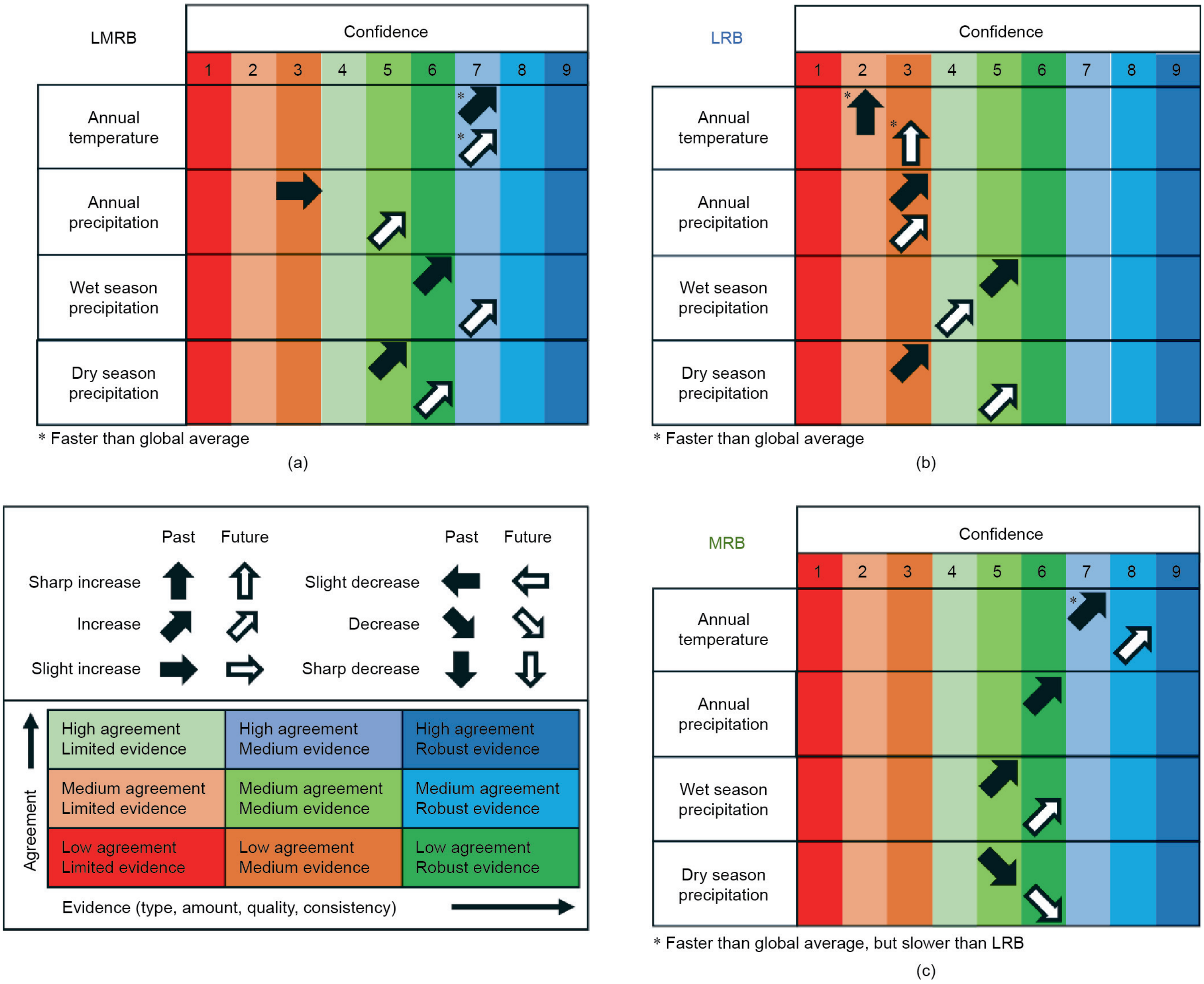
2.2. Uncertainty in estimated past and projected future precipitation

Previous studies have reported moderately increasing trends in annual precipitation over the LMRB in recent decades (low confidence), accompanied by increased temporal variability [22]. A recent study also reported a wetter but insignificant ($p > 0.05$) trend of an increased 24.8 mm·decade^{-1} in annual precipitation over the LMRB during 1983–2016 based on daily gridded (0.25° × 0.25°) precipitation data extracted from the precipitation estimation from remote sensing information using an artificial neural network-climate data record (PERSIANN-CDR) [6]. From 1981 to 2007, annual precipitation calculated using the daily gridded (0.25° × 0.25°) Asian precipitation-highly resolved observational data integration toward evaluation of water resources (APHRODITE) data showed a significant ($p < 0.05$) increasing trend of

52.6 mm·decade^{-1} over the MRB [7]. Similarly, a significant increase (14.5 mm·decade^{-1}) in annual precipitation over the LRB during 1981–2010 was found based on *in situ* precipitation records at seven meteorological stations [14]. These findings imply that, while there are substantial differences in the estimates based on different datasets, annual precipitation in the LMRB has been increasing in the recent past. The use of various different global climate model (GCM) or regional climate model (RCM) outputs, as well as downscaling methods, could have certain impacts on climate change assessment. In addition, the results could vary depending on carbon dioxide (CO_2) emission levels, as considered in the representative concentration pathways (RCPs) [23].

Employing the gridded (0.25° × 0.25°) monthly data from the Global Precipitation Climatology Center (GPCC), long-term (1901–2013) trend analysis has identified decreases in seasonal precipitation for spring (March–May) and summer (June–August) across the LRB, as well as for summer and fall (September–November) over the MRB [24]. For a relatively recent period (1980–2010), Fan and He [14] reported an increasing trend of 8.3 mm·decade^{-1}, only in spring precipitation and over the LRB, by utilizing the monthly precipitation time series measured at seven stations. In addition, a recent study by Chen et al. [25] based on the APHRODITE dataset concluded that, over the entire LMRB, the wet season (May–October, covering the summer months) became wetter by 28 mm·decade^{-1}, and the dry season (November–April, covering the winter months) became drier by 138 mm·decade^{-1} during 1998–2007. Moreover, APHRODITE monthly precipitation data over the LMRB showed increases for July and August (both covered by the wet season) during 1981–2010, while there were small decreases for June and October (covered by the dry season) [7]. These varied estimates indicate a moderate confidence level [13] of changes in precipitation for both the wet and dry seasons in the LMRB (Fig. 1).

There is a consensus, with high confidence, that there will be significant increases in annual precipitation across the LMRB over the next 30–50 years [18]. Variability in annual precipitation is also projected to increase over this basin [17,19,26]. Such a high confidence level of projected wetting trends is primarily due to the indisputable future global warming, which will likely intensify water vapor transport from the Indian Ocean and the Western Pacific Ocean toward the LMRB, resulting in more precipitation across the basin [27]. Depending on the emissions scenario, the projected wetting trends in annual precipitation over the LMRB range from 2.5%–8.6% (under IPCC's Special Report on Emissions Scenario (SRES) A1b) to 1.2%–5.8% (SRES B1). Annual precipitation is also expected to increase by 35–365 mm (3%–14%) over the MRB



(a)

(b)

(c)

Fig. 1. Changes in temperature and precipitation over (a) the LMRB, (b) the upper part of the LMRB (the LRB), and (c) the lower part of the LMRB (the MRB), based on the published literature. See Table S1 for more details and the guidance note of the IPCC for the definitions of the different levels of confidence, evidence, and agreement [13].

by 2050 [20] and by approximately 10% over the LRB under the 2 °C warming scenario [17]. Monthly precipitation is projected to increase over the LRB for all months by 20%–60% under the 2–6 °C warming scenarios, except for April, which shows a projected 16%–40% decrease [17]. With moderate confidence, precipitation is expected to increase during the wet season (May–October) over the MRB by 2050, but is projected to decrease in the dry season (November–April) [20]. Moreover, precipitation will likely experience an elevation shift from high to low altitudes; for example, the annual precipitation of 1500 mm that was historically recorded at an elevation of about 280 m would be observed at elevations of about 80 m [20].

3. Water resources in the LMRB: Historical changes and future projections

3.1. Surface water

A general downward trend in annual streamflow was found in the LMRB over the time period of 1960–2010, but no clear trend was detected after 2010 [24], although the confidence of such a trend is low. Most studies found a decreasing trend in historical streamflow in the LMRB, while a few studies showed the opposite—that is, an increasing trend in streamflow—due to the differing data and methods applied in each study. A detailed literature review on historical runoff changes is provided in Appendix A Table S2.

The changes in streamflow are due to the combined impacts of climate change and human activities. The contributions of influential factors vary over different regions and time periods. Climate change was a key driver of the streamflow alterations in the LMRB before 2010, while human activities—mainly dam construction—contributed more after 2010. This finding has been confirmed by both observational [28] and modeling [29] studies. Climate change dictated the changes in annual streamflow during the transition period of 1992–2009 with a contribution of 82.3%, while human activities contributed 61.9% of the changes in the streamflow in the post-impact period of 2010–2014 [28]. In terms of annual streamflow and water-level variations, the hydrological response of the LRB is considered to be more sensitive to climate factors than to human activities when compared with the MRB [30]. This disparity also highlights the accelerating impacts of intensive human activities on the hydrological processes in the area, especially throughout the MRB in recent years [29].

Differences in the change ratio of streamflow exist between the LRB and MRB because the hydrological systems of these two regions are naturally controlled by different climatic processes [31]. The flow regime in the LRB is influenced more by precipitation and snowmelt, while the flow regime in the MRB is controlled by intense monsoon-season rainfall [32]. Climate-induced changes in precipitation increased the streamflow in the LRB [33], while a slightly decreasing trend was found in most of the MRB due to the combined effects of climate change and human activities for the period 1960–2014 [28]. In the LRB, the magnitude and frequency of flood events were found to increase during the period 1961–2001, and this trend is expected to continue throughout the 21st century from 2011 to 2095 [34]. However, the flow regulation by dams in the LRB will potentially reduce such a positive trend in climate-change-induced flood events [35].

The river flow in the main stem of the LMR is characterized by an inherently strong seasonal cycle due to clear and regular dry–wet transitions. Accordingly, the streamflow seasonality was found to decrease after dam construction in the mainstem of the river [31]. Reservoirs store water in wet seasons and release it during dry seasons, thereby altering the flow regimes [36]. The amplitude of the streamflow has generally increased prior to dams being constructed, while a decreasing trend in maximum flows has been found following the completion of dams upstream [28,37]. Dam operation in the basin reduces the flow in wet seasons but increases the streamflow in dry seasons, thus attenuating flow seasonality [29,38]. A study based on observed discharges showed that the cascade of dams in the Lancang River has increased discharge in the dry season by 34% to 155% on average and has reduced discharge in the wet season by 29%–36% at the Chiang Saen station from 1985 to 2010 [39]. In one of the most important tributaries in the LMRB—that is, the Srepok, Sesan, and Sekong (“3S”) basin, which contributes the most out of all the tributaries to the Mekong River’s discharge—the flow is found to have increased (decreased) by 63%–88% (22%–24.7%) in the dry (wet) season between 1986 and 2005 due to dam construction [40,41]. The annual discharge of the 3S basin is projected to increase by 10.7%, 14.8%, and 13.9% under Representative Concentration Pathway 4.5 (RCP4.5) for the 2030s, 2060s, and 2090s, respectively, compared with the baseline period of 2000–2005 [42].

Despite the decrease in streamflow seasonality, streamflow variability has been found to have increased in the dry season along the river from upstream to downstream due to the combined effects of different reservoir operation plans and land cover changes in the LMRB [38,43]. Consequently, flood amplitude, duration, and the maximum water level have decreased throughout the basin [28,31,32], causing a significant delay in the start, peak, and end of the seasonal flood pulse [39]. These changes in the flood dynamics are expected to amplify if many of the large, planned dams are constructed in the mainstem of the Mekong River, and will particularly affect the flood dynamics in the Tonlé Sap Lake and Mekong Delta systems [44]. Such changes in the flood pulse can help to prevent flood disasters, but can have potential impacts on aquatic biodiversity [45]. Aside from dam construction-induced changes in the flow regime, large-scale atmospheric processes such as radiation, convection, and aerosol movement increased the likelihood of extreme floods and low flows during the 1924–2000 period [31].

Along with climate change and dam construction, other human activities such as irrigation and cropland expansion have altered the water resources in the LMRB. Studies have shown that, although basin-scale average changes in streamflow due to cropland expansion and irrigation are small, changes over highly irrigated areas—mostly in the downstream region of the MRB—are significant [36]. The total water withdrawal from the entire LMRB has been reported to be approximately 62 km^3—that is, 13% of the average annual discharge—of which Vietnam, Thailand, China, Laos, Cambodia, and Myanmar account for approximately 52%, 29%, 9%, 5%, 3%, and 2%, respectively [46]. On average, surface water withdrawal accounts for 97% of the total water withdrawal from the basin, while groundwater withdrawal represents 3% of the total water withdrawal [46]. In the MRB, approximately 80%–90% of water abstractions is utilized for agriculture, but the annual water utilization for agriculture is still less than 4% of the total annual streamflow in this region [47].

Despite the use of different climate forcing and models, studies project—with high confidence—an increasing trend for streamflow in the LMRB; however, the flow regime is highly susceptible to different drivers, such as dam construction, irrigation expansion, land-use change, and climate change. Substantial changes are expected in both annual and seasonal flow, along with a general increasing trend [38,48]. Although hydropower development exhibits a limited influence on total annual flows, it has the largest seasonal impact on streamflow, with an increase in the dry season and a decrease in the wet season, outweighing the impacts of the other drivers [48]. One study showed that climate change may increase the annual streamflow by 15%, while irrigation expansions would cause a slight decrease in the annual streamflow of 3% over the period of 2036–2065 compared with the period of 1971–2000. This study was based on statistically downscaled data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and used a distributed hydrological model, VMod, with a spatial resolution of 0.5 degrees (~50 km at the equator) [48]. The changing ratio in the dry season (+70%) exceeds the changing ratio in the wet season (–15%). In the 3S tributary, the streamflow is projected to increase by 96% in the dry season and decrease by 25% in the wet season, which indicates a higher streamflow sensitivity to climate change and human activities in the 3S system than in the entire LMRB [49].

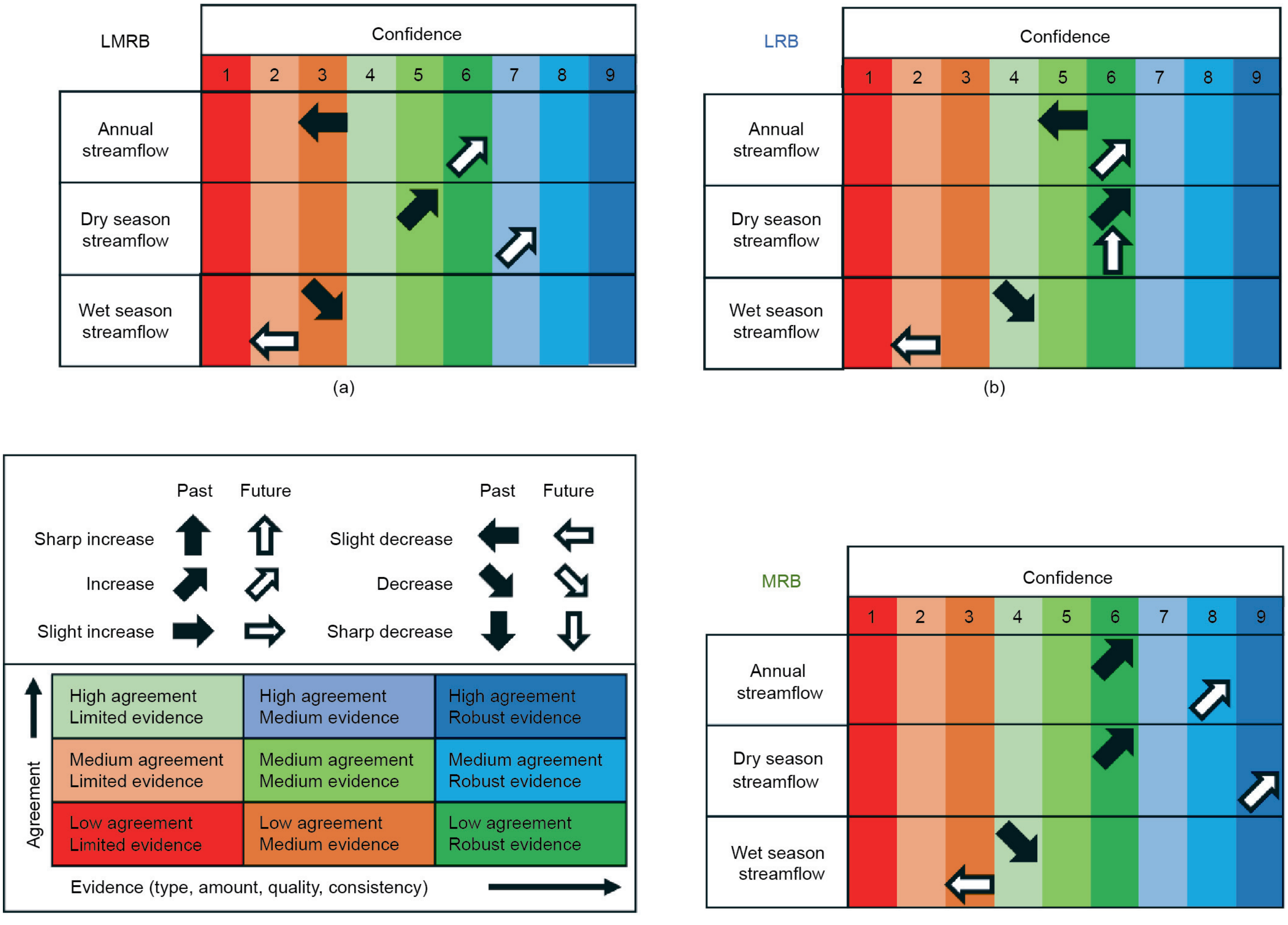
The scenarios for streamflow changes vary spatially, especially in the MRB [50]. Although an increasing trend in streamflow is projected for the LMRB in future, the uncertainties in these projections remain large. Studies based on 11 GCMs show that the annual runoff is projected to increase by 21%, with a range from –8% to 90% by the 2030s in comparison with the historical period (1951–2000) [51]. However, Västilä et al. [21] reported only a 4% increase in annual flow by the 2040s in the LMRB. These authors used dynamically downscaled data from the ECHAM4 climate model to drive a distributed hydrological model Variable Infiltration Capacity (VIC) at a spatial resolution of 25 km. Other studies, based on CMIP5 datasets for the near future (2036–2065), have also reported relatively small changes in mean annual flow ranging from 3% to 10% in the LMRB [21,52].

The magnitude and frequency of extremely high-flow events are projected to increase, while low-flow events are projected to occur less frequently, based on investigations focusing only on the impacts of climate change [52]. More frequent extreme high-flow events could exacerbate flood risks in the LMRB. The massive hydropower construction that induced changes in discharge is expected to have a greater effect on the hydrography than climate change over the next 20–30 years [19]. Furthermore, different patterns of water changes may be present in future in different subbasins of the LMRB. The number of wet days is also projected to increase by the end of the 21st century (2080–2099), which could further increase the flood risk but benefit water utilization in dry periods [53]. The expected changing ratio has been found to be location dependent. For example, Hoang et al. [52] showed that the annual streamflow change in subbasins ranged from +5% to +16%, depending on location, in the period of 2036–2065, in comparison with the baseline of 1971–2000. A detailed summary of changes in historical and future streamflow is shown in Fig. 2.

3.2. Groundwater

Groundwater is a crucial water resource in the LMRB [31]. It connects the farming system, wetland ecology, and livelihood of more than 4.5 million people in the Mekong Delta who rely on the groundwater for drinking [54]. It also plays a critical role in preventing saltwater intrusion [55]. In general, the groundwater in the LMRB has not previously been investigated sufficiently. Only limited information on some local areas within the MRB can be found in the literature related to groundwater resource size, use, and quality [51].

The Mekong Delta extends from central Cambodia to the South China Sea and covers 50 000 km^2 of the fertile alluvial plain [55]. In



(a) (b) (c)

Fig. 2. Changes in streamflow over (a) the LMRB, (b) the LRB, and (c) the MRB, based on published works listed in Appendix A Table S3. Other details are the same as for Fig. 1.

the delta region, more than one million wells have been built to extract groundwater for agricultural, domestic, and industrial needs. Recently, the number of wells in the delta area increased dramatically from the limited number that existed before the 1960s [56]. Based on global groundwater data from the inventory of the International Groundwater Resources Assessment Center (IGRAC), approximately 0.55 km^3 of groundwater was extracted from the LMRB (mainly from the MRB) in 2000 [57]. However, it has been revealed that this number is significantly lower than that reported in country-based statistics [58]. The reason for this difference might be that the groundwater used by individual households across the basin may not have been reflected in the global database from the IGRAC [31].

The groundwater system in the LMRB is primarily affected by the changing hydrological system and by intensive human activities that alter the groundwater balance in terms of recharge and withdrawal [59]. Based on 30 years of monitoring data in the Mekong Delta, a significant decline in the groundwater level was found in this region [55]. In particular, the groundwater level in Ca Mau Province (Vietnam) has fallen by as much as 10 m since 1995 [55]. Groundwater levels have also been observed to be persistently declining in Vietnam at a rate of approximately 0.3 $m{\cdot}a^{-1}$, based on data from nested monitoring wells, causing land subsidence in this region at an average rate of approximately 1.6 $cm{\cdot}a^{-1}$ [60].

The major driving factors of such decreasing trends in groundwater levels can be explained by increased water demand and reduced water supply [55]. Growing populations and expanding agriculture have resulted in a high demand for freshwater; this intensifies the exploitation of groundwater, and the supply of clean water is lower in this region [55]. The reduced groundwater recharge is mainly caused by land-use changes, including a reduction in forests and an increase in the cultivation of fields, where the groundwater recharge ratio is reduced accordingly [59]. Some studies have reported that dams may have a positive impact on the groundwater system due to the artificially controlled, relatively high water level that dams ensure during the dry season [31]. In general, groundwater systems can be impacted by the dynamics of terrestrial water storage due to water impoundment behind dams and can further offset sea-level rise [61], thereby limiting salinity intrusion [62]. Moreover, relatively high groundwater levels due to higher, damming-induced dry-season water levels could benefit irrigation systems in terms of energy cost reduction [31]. In addition to the impacts of multiple factors on groundwater quantity, sea-level-induced saltwater intrusion, agrochemical use, and inherent arsenic pollution affect the quality of groundwater in the region [56,60,63]. The overuse of groundwater has also been found to exacerbate arsenic contamination in groundwater in the Mekong Delta [64], which could be further intensified by climate change [51].

Climate change-induced changes in downstream flood pulse and groundwater recharge patterns are also expected to impact the groundwater system in the LMRB in the future [65]. However, similar to the observed groundwater alterations, projected groundwater information in the LMRB is limited. Shrestha et al. [66] conducted a study on the Mekong Delta and analyzed groundwater change under different RCP scenarios. Their results show that groundwater recharge will decrease at a rate of 3 $mm{\cdot}a^{-1}$ under RCP8.5 and 1.3 $mm{\cdot}a^{-1}$ under RCP4.5 by the end of the 21st century, in comparison with the groundwater recharge in 2010. Moreover, the groundwater level is projected to decline by 1.5–41.0 m (depending on the location) by the end of the 21st century. This decline could affect groundwater storage in this region [66], although a recent global modeling study has suggested that groundwater recharge under different future warming levels would increase, especially in parts of the MRB [67].

3.3. Potential environmental and social impacts of water resource changes

Substantial changes in the water resources in the LMRB will likely have crucial implications for sustainable water management. Projected changes in the basin flow regime are likely to have negative consequences in many aspects. First, large alterations to flow regimes will create disturbances to aquatic ecosystems by changing the distribution of vegetation, natural habitats of native species, and fish migrations patterns [68–70]. Changes in the flow regime caused by dams are also expected to profoundly alter fish abundance and catch in the lower portions of the MRB, with implications for dietary protein consumption [71]. Decreased streamflow in the river during the wet season could impede the overland water flows that induce the natural sedimentation process on floodplains, affecting flood-recession agriculture. Reduced sedimentation will decrease the nutrients carried by the sediment during flood events, thereby further impacting crop yields [48].

It is estimated that water use in the LMRB will increase significantly due to rapid socioeconomic development and growing populations, which are occurring more rapidly than the increase in available water resources in this area [51]. This could result in growing water security challenges in the near future, with an increase in the number of exposed people due to water stress. In addition, studies have revealed that the hotspot areas of water scarcity tend to travel downstream in regions where flows are significantly regulated by dams [72].

The demand for groundwater in the LMRB is expected to increase dramatically under climate change, since surface water is projected to likely become less accessible, intensifying the groundwater withdrawal in this region [51]. Intense extraction of groundwater could also result in large-scale land subsidence, which could lead to the release of arsenic in deep groundwater through vertical migration [73]. This will limit crop yields and pose serious human health risks in the future [74].

In addition to the negative effects of an altered water system, some positive impacts should be mentioned. For example, the increase in streamflow during the dry season [29] could effectively help to overcome water stress for agriculture [75]. The relatively high water level during the dry season allows for the prevention of saltwater intrusion downstream, especially in the Mekong Delta [3,65]. Furthermore, relatively low, dam-induced water levels during the wet season are likely to result in lower flood risks along the river, especially in the main floodplains on the Mekong Delta [44].

4. Knowledge gaps and future research opportunities

4.1. Impacts of dams on river flow and local communities

Dams and their impacts have become a hot topic under frequent discussion in the scientific literature and public media [76], which often leads to controversies. In the LMRB, dams provide multiple services for local communities, including irrigation, hydropower, and navigation facilities, of which hydropower—the colossus of the renewable energy world—draws the most attention [4]. Since the vast hydropower potential of the river system has been exploited to a limited extent so far, especially in the MRB, the MRB countries are undertaking ambitious plans to develop large-scale hydropower projects [77]. Hydropower helps to meet the rising energy demand and promotes economic development in riparian countries [78]. However, it also has negative impacts on the environment and local livelihoods. Such impacts arise from the direct and profound alteration of flow regimes, inundation patterns, and sediment processes downstream [2].

Furthermore, many hydropower development activities have focused on energy benefits without considering the numerous and long-lasting implications to local livelihoods and ecosystem services. With the impacts of the relatively small number of mainstem dams already being felt downstream [29,79], it is crucial to gain an improved understanding of how the development of a large number of planned dams would affect downstream societies and ecosystems. One such area is the Tonlé Sap Lake region, where ecosystems and local livelihoods largely depend on the unique flow reversal in the Tonlé Sap River that is made possible by the flood pulse in the mainstem Mekong River [80]. This flow reversal might cease if many of the projected dams are built [44]; however, there is a lack of a quantitative understanding of the compounded downstream effects of climate change and upstream dams.

4.2. The water–energy–food–ecology nexus

The water–energy–food (WEF) nexus has attracted attention in recent years due to its potential to help develop an understanding of synergies and tradeoffs in an interdisciplinary way among the many frameworks or paradigms for promoting sustainable development [81]. Many studies have taken the WEF nexus approach to improve the understanding and quantification of the supply and demand of the natural resources, economic flows, and social structures that affect water, energy, and food securities in the LMRB [82]. The burgeoning population in this region, accompanied by rapid socioeconomic growth, is expected to cause a surge in demand for water, energy, and food, posing additional challenges for regional sustainability in the future [83]. The WEF nexus will be a promising paradigm to address these challenges. However, achieving WEF securities takes more than just addressing the demand and supply dynamics. More attention needs to be paid to sustaining and restoring the ecosystems that support the provisioning of natural resources in order to maintain societal resilience and ecological well-being [84].

The main goal of the WEF nexus is to integrate water, energy, and food securities, all of which depend on the capability of human societies to organize themselves in such a way as to manage natural resources. Water, energy, and food security can negatively interact with other environmental factors, such as biodiversity and ecosystem services, thereby threatening the long-term sustainable supply of natural resources [85]. Furthermore, ecological well-being is crucial in order to safeguard healthy landscapes that provide a balance of the functions that support the provision of sustainable resources [86]. Therefore, ecology is a promising factor for improving water, energy, and food securities, and should form a fourth fundamental dimension of a novel water–energy–food–ecology (WEFE) nexus framework. The key principles of this new paradigm are to integrate the role of ecology into nexus thinking and to engage local communities in nature-based solutions.

4.3. Groundwater assessment and human health

Groundwater, which supplies drinking water, industrial water use, and irrigation, has been considered a critical water resource in the LMRB, especially in the Mekong Delta region, as a supplement to surface water resources [55]. In Cambodia and Thailand, groundwater is even used as a major water resource for drinking water supply [87]. Moreover, increased groundwater exploitation is occurring due to growing industrial and agricultural uses [58]. However, studies on groundwater resource assessments have received far less attention than studies on surface water systems [31]. Only limited information exists on the extent and size of the aquifer systems around the Mekong Delta [51].

The demand for groundwater has substantially increased in the LMRB due to the rapid socioeconomic development in recent years and the reduction in surface water resources as a result of climate change and anthropogenic activities [55]. In some regions, the overexploitation of groundwater, together with climate change, has already caused widespread environmental problems, such as water-quality deterioration, saltwater intrusion, and aquifer storage depletion [56,60,63,65,74]. The compounded effects on the groundwater system might be far more complex. In addition, overuse of groundwater has been found to exacerbate arsenic contamination in groundwater, causing serious health problems in parts of Cambodia and Vietnam [88,89]. Most likely, climate change will further exacerbate these arsenic problems [90,91]. Therefore, a holistic and thorough analysis of water resources that integrates groundwater and human health is both necessary and imperative in order to provide a clear picture of the multitude of hydrological, ecological, health, and socioeconomic effects that may be imminent under a changing climate, socioeconomic growth, and shifts in water management.

4.4. Transboundary collaboration to address sustainable development goals

Acting toward sustainable development goals (SDGs) is of great importance for the LMRB, where approximately 40% of people in the region live in poverty [4] and 70% of the people in the Mekong Delta suffer from safe water shortage [92]. Efforts have been made in recent years by the riparian countries in the basin to implement SDGs, including ① the Water Resources Management Strategic Plan 2015–2026 for SDG 6 (Clean Water and Sanitation); ② the 20-Year Integrated Energy Plan for SDG 7 (Affordable and Clean Energy); and ③ the Climate Change Master Plan 2015–2036 for SDG 13 (Climate Action) [93]. The LMRB is still far from meeting most of the SDGs, particularly SDG 3 (Good Health and Well-Being), SDG 9 (Industry, Innovation, and Infrastructure), SDG 2 (Zero Hunger), and SDG 1 (End Poverty) [94].

In the LMRB, water links most of the SDGs and plays a central role in the interactions between SDGs (both tradeoffs and synergies), such as energy, food, and health [4]. However, the basin faces numerous challenges for sustainable regional development because of varying water supply and demand among the riparian countries, as well as differences in their interest in basin management and infrastructural development, such as the construction of large-scale hydropower dams. This has made the LMRB one of the most contested international river basins in the world. These challenges underscore the need for an effective cooperation mechanism and a water resource development plan to avoid disputes over water benefits-sharing among stakeholders [95]. This situation, by far, could be the biggest obstacle to achieving SDGs in the LMRB. Therefore, transboundary cooperation, involving policy interventions from different ministerial remits, is necessary in order to strengthen synergies among stakeholders and align their agenda toward achieving SDGs in the basin.

5. Summary

In this paper, we presented a comprehensive review of the existing body of literature addressing changes in the climate and water resources in the LMRB under unequivocal global warming for both historical and future periods. We conclude that there is a critical need to better understand the changing climate and hydrological systems in the LMRB and the socioeconomic and ecological consequences of achieving SDGs in the LMRB, which features a high density of human activities, vulnerable infrastructure, and poor land-use management and practices. Despite the tremendous progress that has been made in understanding both the climatological and hydrological features of the LMRB, scientific communities, societies, and governments are still in need of theoretical and practical knowledge that can help mitigate regional and/or global environmental change while improving socioeconomic and environmental sustainability. Some of the biggest and most pressing challenges are related to the following urgent tasks include: ① investigation of the impacts of dams on river flow and local communities; ② implementation of a novel WEFE nexus; ③ integration of groundwater and human health considerations into water resource assessment and management; and ④ strengthening of transboundary collaboration in order to address SDGs. To cope with and overcome these serious challenges, international collaborations among governments, scientists, and the public are critically important. Such collaborations must generate new knowledge based on an interdisciplinary "web" model, instead of a disciplinary "tree" model, in order to play a key role in moving toward achieving SDGs in the LMRB [96].

This review is based on existing articles, which implies that the outcome of the assessment depends on what is publicly available. As an example, it would be desirable—if the literature allows—to perform an analysis that separates the natural and regulated flow. However, a limited number of articles exist on future projections regarding the natural and regulated flow in the LMRB. Future studies could focus on developing a comprehensive analysis of the individual and compounded effects of climate change and dams on water resources, ecosystems, and societies, with a particular emphasis on upstream–downstream linkages, which are crucial for transboundary water management and regional sustainability within the LMRB.

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Compliance with ethics guidelines

Junguo Liu, Deliang Chen, Ganquan Mao, Masoud Irannezhad, and Yadu Pokhrel declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2021.06.026.

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