



Climate change and irrigation expansion reshape the water pressure and upstream–downstream interactions in the Lancang–Mekong River Basin

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Abstract. In transboundary river basins, water resource pressure results from the combined effects of internal water use growth, external transboundary withdrawal, and climate change, yet the relative contributions of these drivers to both water pressure and upstream–downstream interactions remain poorly quantified. To address this issue, this study adopts the Pressure–State–Response analytical framework to explicitly disentangle and characterize the spatiotemporal patterns and evolution of irrigation water withdrawal pressure in the Lancang–Mekong River Basin under the climate change. Results indicate that the proportion of irrigation water withdrawal relative to available water exhibits a persistent increasing trend. Under the SSP5-8.5 scenario, this proportion is projected to rise to 19% annually and 59% during the dry season by 2040. The impact of irrigation water withdrawal on downstream water availability is significantly greater than that on upstream regions, particularly during the dry season. In the historical period, internal irrigation water withdrawal pressure dominates in Subregions 1 (China), 8 (primarily in Thailand), and 13 (primarily in Vietnam), exceeding external pressure from upstream irrigation water withdrawal, whereas external irrigation-induced water appropriation is the primary driver in the remaining subregions. Under future climate scenarios (2021–2040), both internal and external irrigation pressures intensify across the basin, exhibiting pronounced nonlinear dynamics and spatial heterogeneity. Notably, Subregion 8 undergoes a structural shift in dominant pressure, transitioning from internally driven irrigation pressure in the historical period to externally driven irrigation appropriation in the future. Meanwhile, the growth rates of irrigation water withdrawal pressure are redistributed spatially: compared to the historical period, the growth of external irrigation pressure slows in downstream subregions (9–13), while it continues to increase in midstream and upstream subregions (2–8). The analysis aims to identify vulnerable components of the basin system, clarify transboundary responsibility allocation, and support differentiated water governance strategies.

1 Introduction

Irrigation water use accounts for the largest share of consumptive freshwater use globally and constitutes one of the most direct anthropogenic drivers of basin-scale hydrological change (Döll and Siebert, 2002; Tian et al., 2025). Under ongoing climate warming, alterations in the spatiotemporal distribution of precipitation, increased evapotranspiration, and changes in



30 runoff seasonality are modifying basin-scale water availability and demand, thereby intensifying irrigation-related pressure on water resource systems. In transboundary river basins, such pressure is not only generated by local water use growth but is also propagated and potentially amplified through upstream–downstream connectivity within river networks, leading to complex patterns of water competition across regions. Consequently, it is estimated that between 290 million and 1.13 billion people worldwide are affected by irrigation-induced water stress in transboundary river basins (Munia et al., 2016).

35 The Lancang–Mekong River Basin is one of the world’s most representative transboundary river systems, with water resources that are critical for agricultural production across riparian countries. Approximately 90% of irrigation water use in these countries depends on the river, supporting the livelihoods of hundreds of millions of people (Li et al., 2019). However, the basin is highly sensitive to both climate change and human activities. Recent studies indicate that the regional warming rate exceeds the global average, while precipitation and runoff exhibit pronounced spatiotemporal variability. Declining
40 discharge trends have already been detected at several hydrological stations, with potential implications for irrigation water availability (Liu et al., 2022; Zhang et al., 2023). At the same time, anthropogenic pressures have further intensified water stress across the basin. Agricultural expansion has continued, resulting in a dense irrigation network that currently encompasses approximately 4 million hectares of cultivated land and more than 11 000 irrigation projects, with the irrigated area projected to expand to around 6 million hectares by 2030. Together with rapid hydropower development, these changes have increased
45 the complexity and uncertainty of irrigation water supply conditions throughout the basin (Li et al., 2017; Morovati et al., 2024; Wang et al., 2023).

Accordingly, substantial research efforts have been devoted to investigating water stress and its driving mechanisms in transboundary river basins (Chen et al., 2020; Do et al., 2020; Tian et al., 2020). Despite these important contributions, existing studies have largely focused on individual stressors or localized spatial scales, and systematic quantification of the relative
50 contributions of intra-basin irrigation expansion and upstream competitive water appropriation in transboundary river basins remains limited. Consequently, the dominant sources of irrigation water withdrawal pressures across subregions and their spatiotemporal evolution are still not well understood. Under future climate scenarios, mismatches between irrigation water demand and available water supply are expected to intensify, while the relative roles of upstream competition and local water-use intensity may undergo substantial shifts (Wang et al., 2021; Yu et al., 2024). Such simplified attribution obscures the multi-
55 driver nature of water stress and can introduce structural biases into basin-scale water resource assessments. These biases, in turn, hinder responsibility allocation and the formulation of differentiated governance strategies in transboundary river basins, particularly under future climate change scenarios where the balance between internal water-use expansion and external upstream pressures is likely to change.

To systematically elucidate the mechanisms underlying the formation and evolution of water resource stress, a number
60 of integrated analytical frameworks have been proposed. Among them, the Pressure–State–Response (PSR) framework has been widely adopted in water resource system studies due to its clear causal structure linking human activities, changes in water resource conditions, and societal management responses (Zhang et al., 2025). Compared with single-indicator or static assessment approaches, the PSR framework enables structured decomposition of water resource stress, allowing systematic

identification of its sources, pathways, and potential intervention points. Previous studies have demonstrated its applicability
65 not only at local scales but also its strong potential for basin-scale analysis (Hazbavi et al., 2020).

Building on this, this study develops a PSR analytical framework to systematically elucidate the evolutionary dynamics
of irrigation-induced water resource stress in the Lancang–Mekong River Basin. Within this framework, climate change and
upstream irrigation-induced water appropriation are treated as the primary pressure drivers, regional water availability is
represented as the core state variable, and system responses are characterized by irrigation water stress types. Using this
70 framework, we analyze the spatiotemporal patterns and evolution of irrigation pressures at both annual and seasonal scales,
with particular attention to shifts in dominant stress regimes and the reorganization of their growth trajectories. Furthermore,
a basin-scale subregional irrigation water withdrawal pressure types classification framework is developed by integrating
internal and external irrigation pressure changes and dominant pressure. This integrated approach aims to advance
understanding of the nonlinear evolution of irrigation water withdrawal stress and the resilience of transboundary river basin
75 systems.

2 Materials and methods

2.1 Study area

The Lancang–Mekong River Basin is not only an important transboundary river system of the Indochina Peninsula but
also one of the most important agricultural regions in the world. Over the past four decades, the irrigated area in the Lancang–
80 Mekong Basin has exhibited a sustained expansion (Figure 1), with a multi-year average of approximately 27,000 km². During
2020–2024, the irrigated area reached its maximum, about 43,000 km². The period 2000–2009 experienced the most rapid
growth compared with 1990–1999, with an increase of up to 56%, whereas the growth rate slowed considerably to 15% during
2010–2019. Notably, the recent period (2010s–2024) shows a renewed upward trend, with a cumulative increase of 21%.
Agricultural land is projected to expand by 65% by 2060 (Morovati et al., 2024), with surface water expected to supply 97%
85 of irrigation demand (AQUASTAT, 2014; Tatsumi and Yamashiki, 2015).

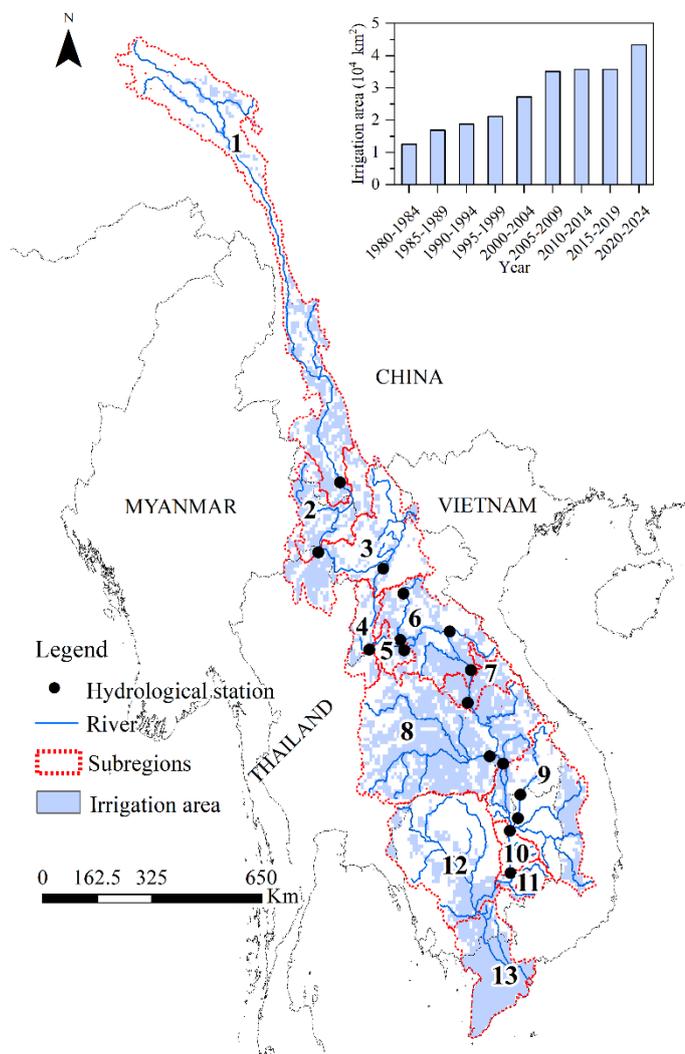


Figure 1: Hydrological stations, river network, irrigation areas, and subregions in the study area

2.2 Data sources and preprocessing

The datasets used in this study include meteorological variables (precipitation and potential evapotranspiration), hydrological and hydraulic data (runoff, irrigation canals, and reservoir operations), and land-surface characteristics (soil types, vegetation indices, and spatial distribution of irrigated areas).

Historical meteorological data for the period 1980–2024 were obtained from the ERA5-Land dataset and were used to estimate agricultural irrigation water demand, calibrate climate projections from the Coupled Model Intercomparison Project Phase 6, and drive the hydrological model. ERA5-Land provides precipitation, temperature, and potential evapotranspiration variables at a spatial resolution of 0.1° . Given the potential uncertainties in precipitation and evapotranspiration estimates, ERA5-Land precipitation and potential evapotranspiration (PET) were bias-corrected using historical observations from 110

meteorological stations distributed across the basin for the period 2000–2020, applying a monthly scaling coefficient method.

Future climate conditions for the period 2021–2040 were represented using a multi-model ensemble from CMIP6 under three representative Shared Socioeconomic Pathway (SSP) scenarios: SSP1–2.6 (low-emission), SSP2–4.5 (medium-emission), and SSP5–8.5 (high-emission). Based on performance evaluations for the Mekong River Basin, five global climate models (GCMs) were selected: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL (Eyring et al., 2016; Gidden et al., 2019), ensuring the robustness of climate projections. To enhance the reliability of future climate simulations, CMIP6 outputs were subjected to a rigorous bias-correction procedure. First, bilinear interpolation was applied to downscale the five GCM datasets with varying native resolutions to a unified spatial resolution of 0.1°, consistent with ERA5-Land. Subsequently, a multivariate bias correction method based on N-dimensional probability density function transformation (Multivariate Bias Correction) was employed. This approach uses historical ERA5-Land data as a reference to establish correction relationships with corresponding CMIP6 simulations and applies these relationships to future CMIP6 projections, thereby correcting systematic biases in key climate variables, including precipitation and temperature.

Daily streamflow data were obtained from the China Meteorological Administration and the Mekong River Commission. Observed discharge records from 15 key hydrological stations along the main stem and major tributaries of the Mekong River were used for hydrological model calibration and validation during the period 2000–2020. These stations include Jinghong, Chiang Sean, Chiang Khan, Nong Khai, Nakhon Phanom, Mukdahan, Pakse, Stung Treng, Kratie, Chantangoy, Siempang, Pak Mun, Phonesy, Tha Ngon, and Ban Pak Kanhong.

Irrigation canal network data were derived from high-resolution Google satellite imagery with a spatial resolution of 0.5 m. Irrigation canals were identified using a deep learning–based intelligent remote sensing recognition model. Canal headworks were extracted and treated as irrigation water abstraction points (Zhao et al., 2025). Reservoir data were obtained from the Mekong River Commission and the Mekong Region Futures Institute (2024). The dataset includes reservoir locations, storage capacities, and years of operation.

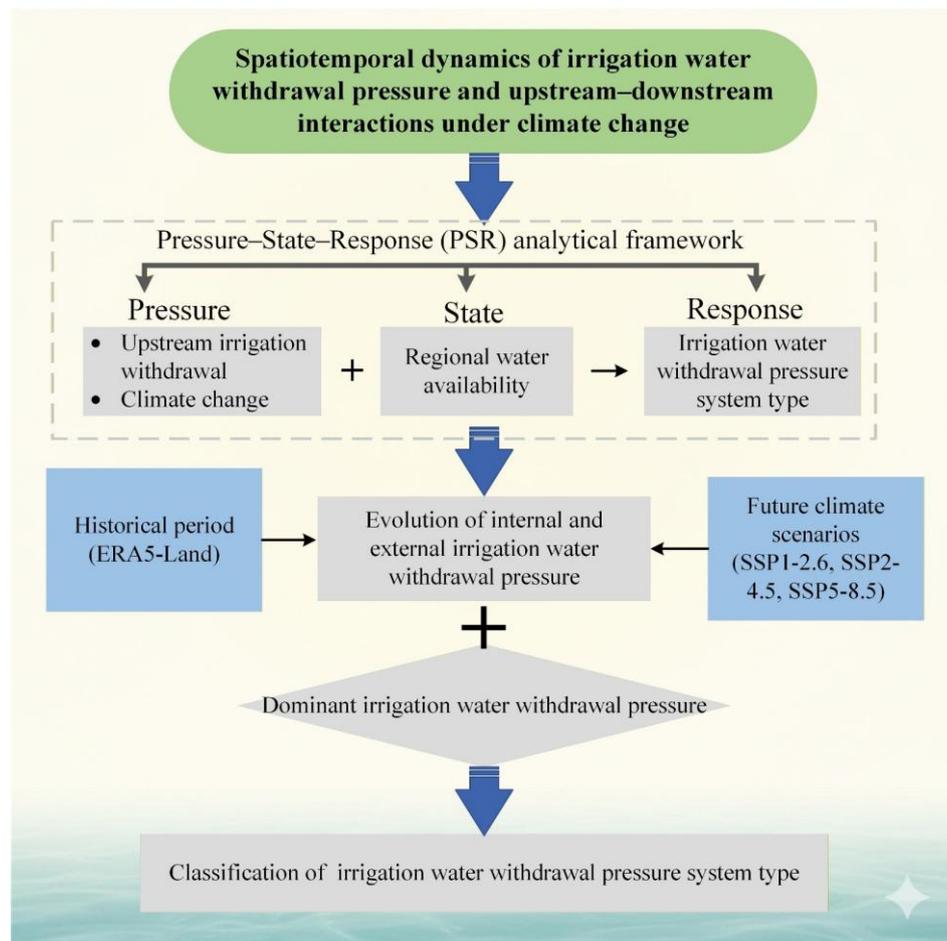
Soil data were obtained from the global soil database of the Food and Agriculture Organization of the United Nations. The dataset has a spatial resolution of 10×10 km. The normalized difference vegetation index (NDVI), leaf area index (LAI), and snow cover fraction were derived from MODIS products. These datasets have a spatial resolution of 500×500 m and a temporal resolution of 16 days. Irrigated area data were obtained from the FAO Global Map of Irrigation Areas dataset. This dataset integrates national and subnational irrigation statistics with geospatial information on irrigation locations and extents. Spatial distributions of irrigated crop types were derived from the SPAM Global dataset. The dataset includes information for 46 crop types and has a spatial resolution of 10×10 km (IFPRI, 2024).

2.3 Methodology

This study employs the Pressure–State–Response (PSR) analytical framework to systematically assess the spatial patterns and evolution of water pressure in the Lancang–Mekong Basin under the combined influences of irrigation water withdrawal and climate change. Upstream irrigation withdrawal and climate change were identified as the primary sources of pressure,



130 while changes in regional water availability were used to characterize the system's state (Figure 2). We defined two pressure
 indicators: (1) internal irrigation water withdrawal pressure (internal irrigation pressure), measured as the proportion of local
 irrigation withdrawal relative to regional available water, and (2) external irrigation water withdrawal pressure (external
 irrigation pressure), measured as the proportion of the reduction in regional water availability caused by upstream irrigation
 withdrawal. Dominant irrigation water withdrawal pressure (dominant irrigation pressure) characteristics for each subregion
 135 were identified by jointly considering these two indicators. Specifically, a subregion is classified as internally dominated if its
 internal irrigation pressure exceeds external irrigation pressure; otherwise, it is categorized as externally dominated. Finally,
 by considering the change of internal and external irrigation pressure along with the dominant irrigation pressure, we define
 the irrigation water withdrawal pressure system (irrigation pressure system) type of each subregion as the system's response.



140 **Figure 2: Schematic diagram of the PSR-based irrigation pressure assessment**

This study calculated monthly runoff and irrigation water withdrawal for each sub-basin of the Lancang–Mekong River Basin for the period 1980–2020. 30% simulated runoff was reserved as environmental flow. The remaining portion was defined as available water. The methods used to simulate runoff and irrigation water withdrawal are described as follows.



(1) Runoff simulation

145 This study utilizes the Tsinghua Representative Elementary Watershed (THREW) hydrological model to simulate daily runoff processes. Rooted in watershed thermodynamic systems theory, THREW simulates the exchange of energy, momentum, mass, and entropy within the system (Tian et al., 2012). The model structures the watershed vertically into surface and subsurface layers, with the surface layer further divided into six sub-layers and the subsurface layer into two sub-layers. It integrates multi-source forcing data, including precipitation, air temperature, potential evapotranspiration, Leaf Area Index, 150 Normalized Difference Vegetation Index, soil properties, land use, and Digital Elevation Model. THREW model has been successfully applied in the Lang-Mekong River Basin (Morovati et al., 2023; Zhang et al., 2023). For this study, the calibration period is defined as 2000–2009, and the validation period as 2010–2020. Model performance is evaluated using the Nash–Sutcliffe Efficiency (*NSE*) coefficient and the Percent Bias (*PBIAS*), calculated as follows:

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_s - Q_o)^2}{\sum_{i=1}^n (Q_o - \overline{Q_o})^2} \quad (1)$$

$$PBIAS = 100 * \frac{\sum_{i=1}^n (Q_o - Q_s)}{\sum_{i=1}^n \overline{Q_o}} \quad (2)$$

In the equation: n is the number of observations; Q_o denotes the observed streamflow; Q_s denotes the simulated 155 streamflow; and $\overline{Q_o}$ represents the mean of the observed streamflow. The closer the *NSE* is to 1 and the *PBIAS* is to 0, the better the simulation performance. Table 1 shows that at all stations, both calibration and validation achieved $NSE > 0.76$ and $PBIAS < 0.02\%$, demonstrating the model’s high reliability.

Table 1: NSE and PBIAS (%) of the THREW model at hydrological stations

Number	Stations	Metrics	Calibration	Validation
1	Jinghong	<i>NSE</i>	0.93	0.79
		<i>PBIAS</i>	0.004	0.01
2	Luang Prabang	<i>NSE</i>	0.94	0.76
		<i>PBIAS</i>	0.003	-0.001
3	Chiang Khan	<i>NSE</i>	0.94	0.70
		<i>PBIAS</i>	-0.0003	0.002
4	Nong Khai	<i>NSE</i>	0.95	0.78
		<i>PBIAS</i>	-0.002	0.006
5	Nakhon Phanom	<i>NSE</i>	0.95	0.89
		<i>PBIAS</i>	0.0001	-0.002
6	Mukdahan	<i>NSE</i>	0.95	0.88
		<i>PBIAS</i>	-0.003	-0.001
7	Stung Treng	<i>NSE</i>	0.92	0.88
		<i>PBIAS</i>	-0.002	-0.002
8	Pakse	<i>NSE</i>	0.94	0.91
		<i>PBIAS</i>	-0.002	-0.001



9	Kratie	<i>NSE</i>	0.94	0.86
		<i>PBIAS</i>	-0.004	-0.002
10	Chantangoy	<i>NSE</i>	0.92	0.91
		<i>PBIAS</i>	-0.007	-0.01
11	Siempang	<i>NSE</i>	0.87	0.88
		<i>PBIAS</i>	0.003	-0.098
12	Pak Mun	<i>NSE</i>	0.93	0.96
		<i>PBIAS</i>	-0.002	0.011
13	Phonesy	<i>NSE</i>	0.91	0.93
		<i>PBIAS</i>	-0.008	0.003
14	Tha Ngon	<i>NSE</i>	0.86	0.81
		<i>PBIAS</i>	0.02	-0.001
15	Ban Pak Kanhoung	<i>NSE</i>	0.86	0.87
		<i>PBIAS</i>	0.002	-0.011

(2) Irrigation water withdrawal estimation

160 This study first integrated spatial datasets using geographic information system (GIS) overlay analysis. These datasets include sub-basin boundaries, agricultural irrigation districts, irrigation canal networks, and crop planting patterns. This process enabled the spatially explicit identification of irrigation abstraction points, the service areas of each irrigation node, and the corresponding crop types.

Based on this information, crop net irrigation water demand was calculated following the crop water requirement approach 165 recommended by the Food and Agriculture Organization of the United Nations. The calculation incorporated potential evapotranspiration, precipitation, and crop coefficient data. Net irrigation water demand (IR) at each irrigation node was estimated by accumulating the monthly differences between crop evapotranspiration (ET) and effective precipitation (P_{eff}). The calculation is expressed as follows:

$$IR = \sum_{j=1}^m (ET - P_{eff}) \quad ET > P_{eff} \quad (3)$$

$$170 \quad IR = 0 \quad ET \leq P_{eff} \quad (4)$$

Where m represents the crop growth season length (months) and j denotes the month index; monthly crop evapotranspiration (ET) is calculated as follows:

$$ET = K_c \times PET \quad (5)$$

K_c denotes the crop coefficient (Allen et al., 1998; FAO, 2019), and PET represents potential evapotranspiration.

175 Effective precipitation is determined via the SCS method (USDA, 1967), with the calculation given by:

$$P_{eff} = \begin{cases} \max(0, f \times (1.253P^{0.824} - 2.935) \times 10^{0.001PET}), & P \geq 12.5\text{mm} \\ P, & P < 12.5\text{mm} \end{cases} \quad (6)$$

P denotes monthly precipitation, and f represents the correction factor.

Following the estimation of net irrigation requirements, actual irrigation water use are calculated by incorporating



180 variations in irrigation efficiency coefficients of different irrigation area (Koponen et al., 2017). Specifically, Actual irrigation
water use is obtained by dividing the net irrigation demand by the corresponding efficiency factors. For scenarios involving
irrigation expansion, the increase in irrigated area is projected based on development plans outlined in MRC reports (Koponen
et al., 2017).

185 Simulated irrigation water withdrawal under historical conditions closely matched reported national irrigation statistics
from the MRC (Koponen et al., 2017). For Laos, Thailand, Cambodia, and Vietnam simulated estimates differed from reported
values by less than 6% (Table 2), which is acceptable for basin-scale irrigation water withdrawal modelling.

Table 2: Comparison between simulated and reported irrigation water withdrawal in 2007

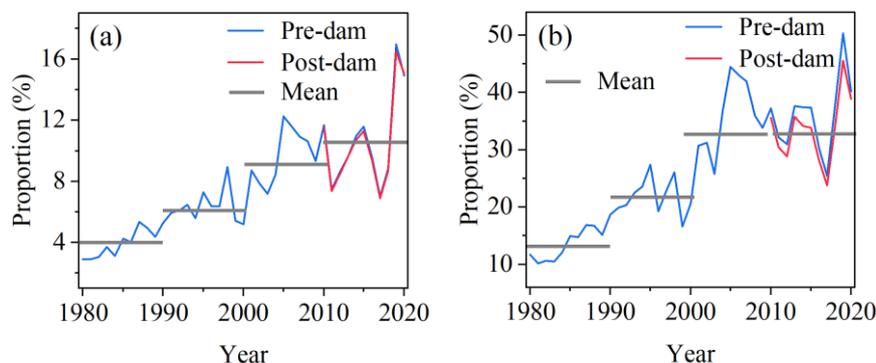
Irrigation water use	Laos	Thailand	Cambodia	Vietnam
MRC (10^8 m ³)	29	84	30	251
Simulation (10^8 m ³)	28	86	28	249
Difference (%)	-4	2	-6	-0.8

3 Results

3.1 Historical spatiotemporal distribution and evolution of internal and external irrigation pressure

3.1.1 Changes in the basin-wide ratio of irrigation water withdrawal to available water

190 The results (Figure 3) show that the proportion of irrigation water withdrawal relative to available water in the basin
increased steadily from 1980 to 2020 at both annual and dry-season scales. This upward trend reflects the combined effects
of a sustained decline in natural runoff since 2000 and a continuous increase in irrigation water withdrawal. Under the no-
reservoir scenario, irrigation withdrawal accounted for an average of 8% of available water on an annual basis and 27%
during the dry season over the period 1980–2020. During 1980–2009, these proportions were lower, at 6% annually and 23%
195 in the dry season. In contrast, during 2010–2020, the dry-season proportion increased markedly to 36%, while the annual
proportion rose to 11%. Following the rapid expansion of reservoir infrastructure after 2010, the reservoir scenario exhibits a
slight moderation of irrigation pressure. Under this scenario, irrigation withdrawal accounted for 10% of available water
annually and 34% during the dry season over 2010–2020.



200 **Figure 3: Proportion of irrigation water withdrawal to available water in the basin: (a) annual scale and (b) dry season**

Decadal statistics indicate that, at the annual scale, the growth rates of the ratio of irrigation water withdrawal to available water were broadly similar during the 1980s–1990s and the 1990s–2000s, each at approximately 3% (Table 3). In both periods, the increase was driven primarily by expansion in irrigation water withdrawal. Based on the irrigation water withdrawal and available water data, irrigation withdrawal rose by 53% in the 1980s–1990s and by 44% in the 1990s–2000s, whereas available water declined by 7% in the former period and remained essentially unchanged in the latter. During the 2000s–2010s, the annual growth rate slowed markedly to 1%, reflecting stable water availability and a much smaller increase in irrigation withdrawal (7%). At the dry-season scale, the growth rate of the irrigation-to-availability ratio peaked at 13% in the 1990s–2000s before dropping sharply to nearly zero in the 2000s–2010s.

Table 3: Percentage growth of basin irrigation water relative to available water over different periods

Time period	Annual	Dry season
1980s–1990s	3	8
1990s–2000s	3	13
2000s–2010s	1	0

210 3.1.2 Spatial heterogeneity of internal and external irrigation pressure across subregions

As shown in Figure 4a, pronounced spatial heterogeneity characterizes the multi-year mean (1980–2020) ratio of irrigation water withdrawal to available water across the 13 subregions of the Lancang–Mekong Basin. The downstream delta region (Subregion 13) exhibits the highest ratios. At the annual scale, irrigation withdrawal account for approximately 4% of available water, increasing to nearly 15% during the dry season. Despite relatively abundant water resources, this region sustains very high absolute irrigation demand, contributing about 56% of total basin-wide irrigation withdrawal over 1980–2020.

The second-highest ratios occur in the midstream region (Subregion 8, mainly in Thailand), with values of approximately 3% annually and 10% during the dry season. The upstream region (Subregion 1, mainly in China) ranks third. Although this subregion accounts for only about 4% of total basin irrigation withdrawal, it contains roughly 10% of basin-wide available



220 water. Consequently, irrigation withdrawal represents a relatively high share of local water availability, indicating pronounced
 internal irrigation pressure.

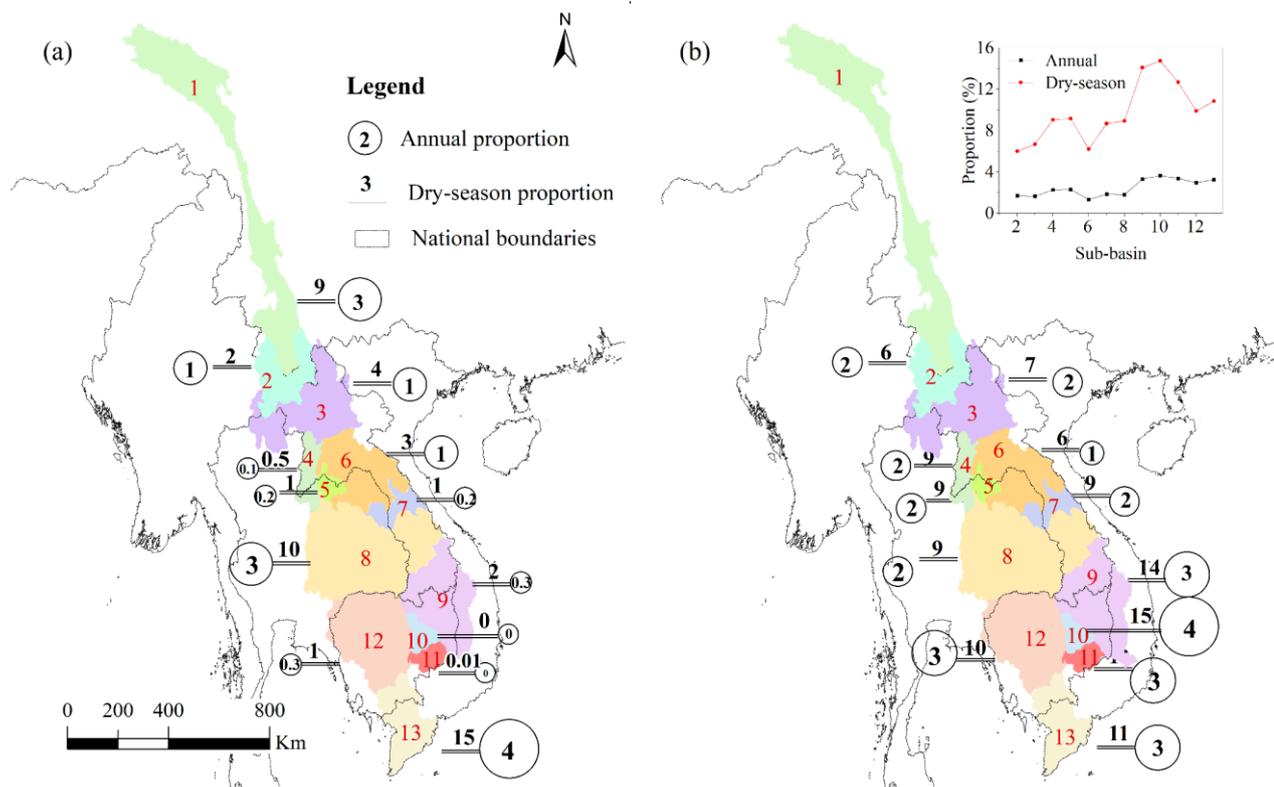


Figure 4: Annual and dry-season ratios of (a) local irrigation withdrawal to available water by subregion (internal irrigation pressure), and (b) upstream irrigation-induced reductions to subregional available water (external irrigation pressure) (1980–2020)

225 Figure 4b shows that the impact of upstream irrigation withdrawal on subregional water availability also exhibits
 pronounced spatial heterogeneity. Downstream subregions are generally more strongly affected than upstream ones, whereas
 impacts in the midstream subregions (7–8) are comparatively lower.

At the annual scale, due to the propagation effect of upstream irrigation withdrawal, available water in the upper- and
 midstream subregions decreases on average by 1%–2%. In the downstream subregions (9–13), the reduction in available water
 230 is larger, reaching about 3%–4%. At the dry-season scale, the influence of upstream irrigation withdrawal is further amplified.
 Available water in the upper- and midstream subregions declines by roughly 6%–9%, whereas in the downstream subregions
 (9–13), the reduction reaches approximately 10%–15%.

Dominant irrigation pressure characteristics were identified by jointly considering internal irrigation pressure and external
 irrigation pressure (Figure 4a,4b). Results indicate that Subregions 1, 8, and 13 exhibit substantially higher proportions of local
 235 irrigation water withdrawal relative to available water than upstream-induced reductions. The irrigation pressure in these



subregions is therefore internally dominated. In contrast, in the remaining subregions are primarily influenced by the propagation of upstream competitive water withdrawal and display a spatial pattern dominated by external irrigation pressure.

3.1.3 Changes in internal and external irrigation pressure across subregions

Considering internal and external irrigation pressure separately, external pressure increased most strongly in the downstream subregions (9–13) during 2001–2020 compared with 1980–2000 (Figure 5). Internal pressure increased most in Subregions 8 and 13. When changes in internal and external irrigation pressure are examined jointly, the multi-year averages for 2001–2020 show that, relative to 1980–2000, 10 out of the 13 subregions experienced increases in both internal and external pressure. Among the subregions, Subregion 13 exhibits the largest combined increase in internal and external irrigation pressure, followed by Subregions 8 and 9. Subregions 10 and 11 are primarily affected by increases in external pressure due to upstream irrigation withdrawal. The upstream-most Subregion 1 shows changes only in internal pressure, with no influence from upstream abstractions.

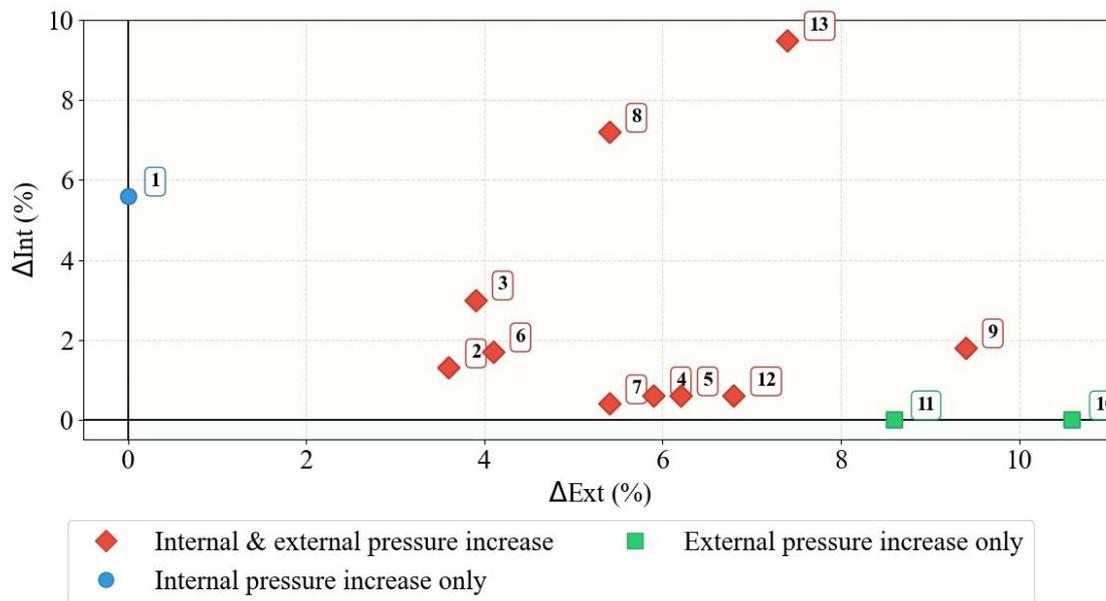


Figure 5: Changes in the internal irrigation pressure (ΔInt) and external irrigation pressure (ΔExt) from 1980–2000 to 2001–2020

3.2 Spatiotemporal distribution and evolution of internal and external irrigation pressure under future climate scenarios

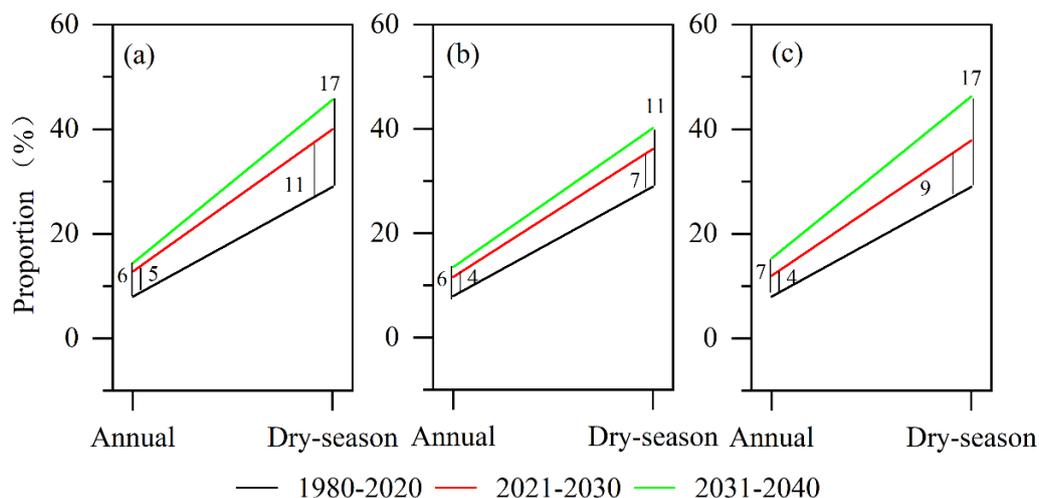
3.2.1 Changes in the basin-wide ratio of irrigation water withdrawal to available water

Compared with the historical period, the proportion of irrigation water withdrawal relative to available water in the basin shows a significant increasing trend under all three climate scenarios, with a particularly pronounced increase during the dry season (Figure 6). At the annual scale, during 2031–2040, the proportion of irrigation water withdrawal under SSP1–2.6,



255 SSP2–4.5, and SSP5–8.5 reaches 14%, 14%, and 15%, respectively. This represents an increase of approximately 6%–7% relative to the multi-year average for 1980–2020. Changes at the dry-season scale are more pronounced. During 2031–2040, the proportion of irrigation water withdrawal under SSP1–2.6, SSP2–4.5, and SSP5–8.5 reaches 46%, 40%, and 46%, respectively, representing an increase of approximately 11%–17% compared with the historical multi-year average. Under the high-emission SSP5–8.5 scenario, by 2040, the annual and dry-season proportions rise to 19% and 59%, respectively.

260 In terms of temporal evolution, 2021–2030 marks the period of the fastest increase in irrigation pressure. Relative to the historical baseline, the annual proportion of irrigation water withdrawal to available water rises by approximately 4%–5%, while the dry-season proportion increases more sharply by 7%–11% across all three scenarios. In 2031–2040, however, the growth rate slows, with annual proportions rising by only 1%–3% and dry-season proportions by 4%–8%, indicating a deceleration in the growth of irrigation pressure.



265

Figure 6: Annual and dry-season ratios of irrigation withdrawal to available water under SSP1–2.6 (a), SSP2–4.5 (b), and SSP5–8.5 (c)

3.2.2 Spatiotemporal distribution of internal and external irrigation pressure across subregions

270 Relative to the historical period, the spatial pattern of internal water pressure in the basin shifts under future climate scenarios. Historically, Subregions 13, 8, and 1 exhibited the highest internal irrigation pressure, with the ranking at both annual and dry-season scales being Subregion 13 > Subregion 8 > Subregion 1. Under future climate scenarios, this pressure pattern is substantially altered (Figure 7a-c). At the annual scale, internal pressure in Subregion 1 increases markedly, approaching or occasionally exceeding that of Subregion 13, while pressure in Subregion 8 declines, becoming the lowest among the three. At the dry-season scale, except under the low-radiative forcing scenario SSP1–2.6, internal irrigation pressure in Subregions 1 and 13 is roughly equal and remains higher than in Subregion 8.

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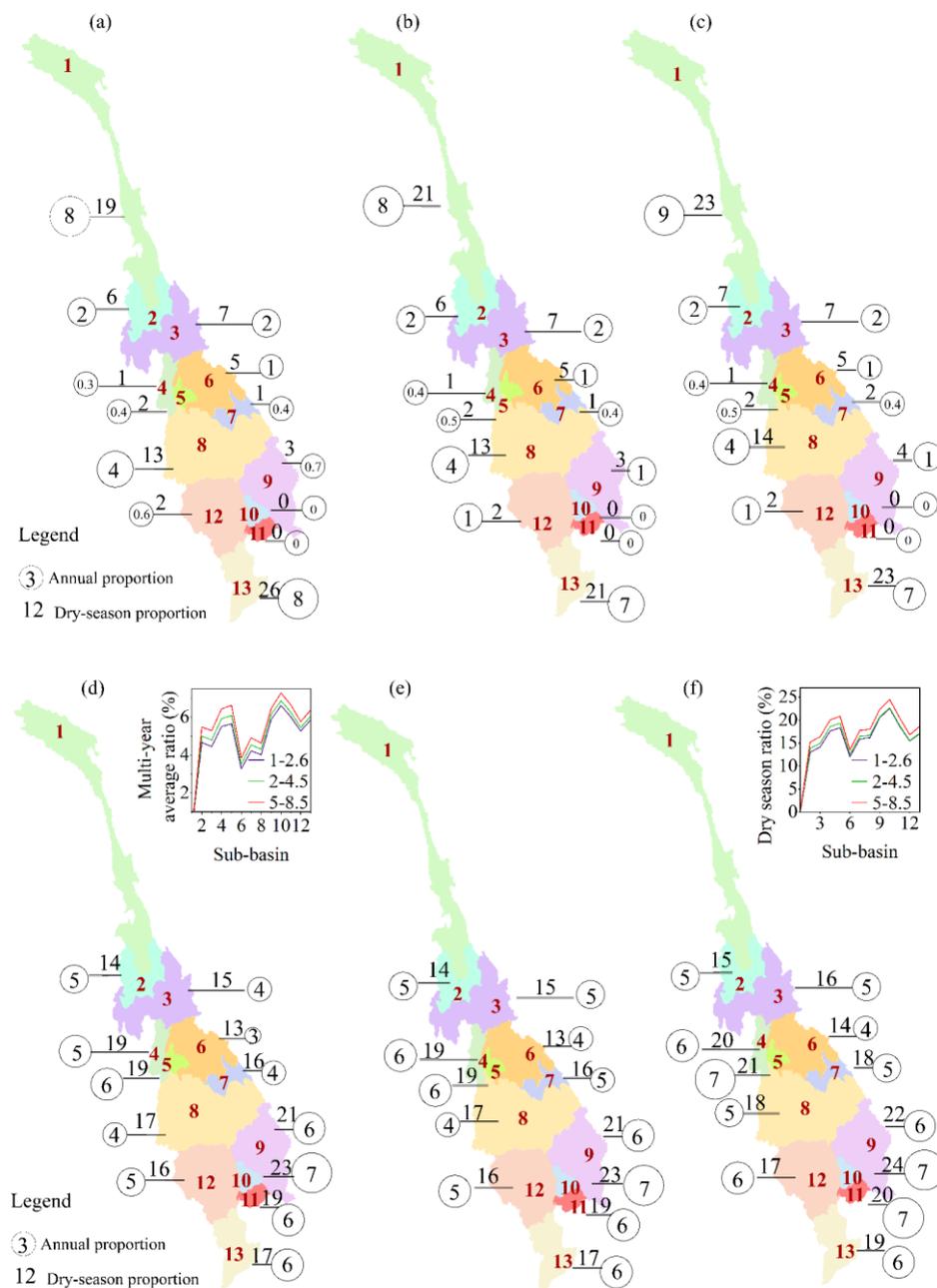


Figure 7: Internal irrigation pressure (a-c) and external irrigation pressure (d-f) under SSP1–2.6, SSP2–4.5, and SSP5–8.5 scenarios

As shown in Figure 7d–f, the spatial pattern of reductions in available water induced by upstream irrigation differs markedly between the historical period and future climate scenarios. At the annual scale, during the historical period, external irrigation pressure was clearly higher in the downstream subregions than in the upper- and midstream subregions. Under the



three future climate scenarios, however, this pattern shifts. Specifically, in the upstream subregions, the proportion of available water reduced by upstream irrigation withdrawal ranges from approximately 4% to 7%, compared with 3%–5% in the midstream subregions and 5%–7% in the downstream subregions. Overall, midstream subregions experience the lowest external irrigation pressure, while upstream and downstream subregions are similar, indicating a relative strengthening of upstream-induced external pressure under future scenarios.

At the dry-season scale, the spatial heterogeneity largely follows the historical pattern. External pressure continues to exhibit the “highest downstream, intermediate upstream, lowest midstream” pattern. Specifically, the proportion of available water affected in the upstream subregions (2–5) ranges from 14% to 21%, in the midstream subregions (6–8) from 13% to 18%, and in the downstream subregions (9–13) reaches the highest values of 16%–24%. Subregions 1, 8, and 13 were primarily dominated by internal irrigation pressure during the historical period (2001–2020) at both annual and dry-season scales, while the other subregions were mainly dominated by external pressure. Under future climate scenarios, Subregion 8 shifts to external dominance, whereas the dominant pressure types in the other subregions remain unchanged, reflecting a structural change in Subregion 8’s water pressure sources.

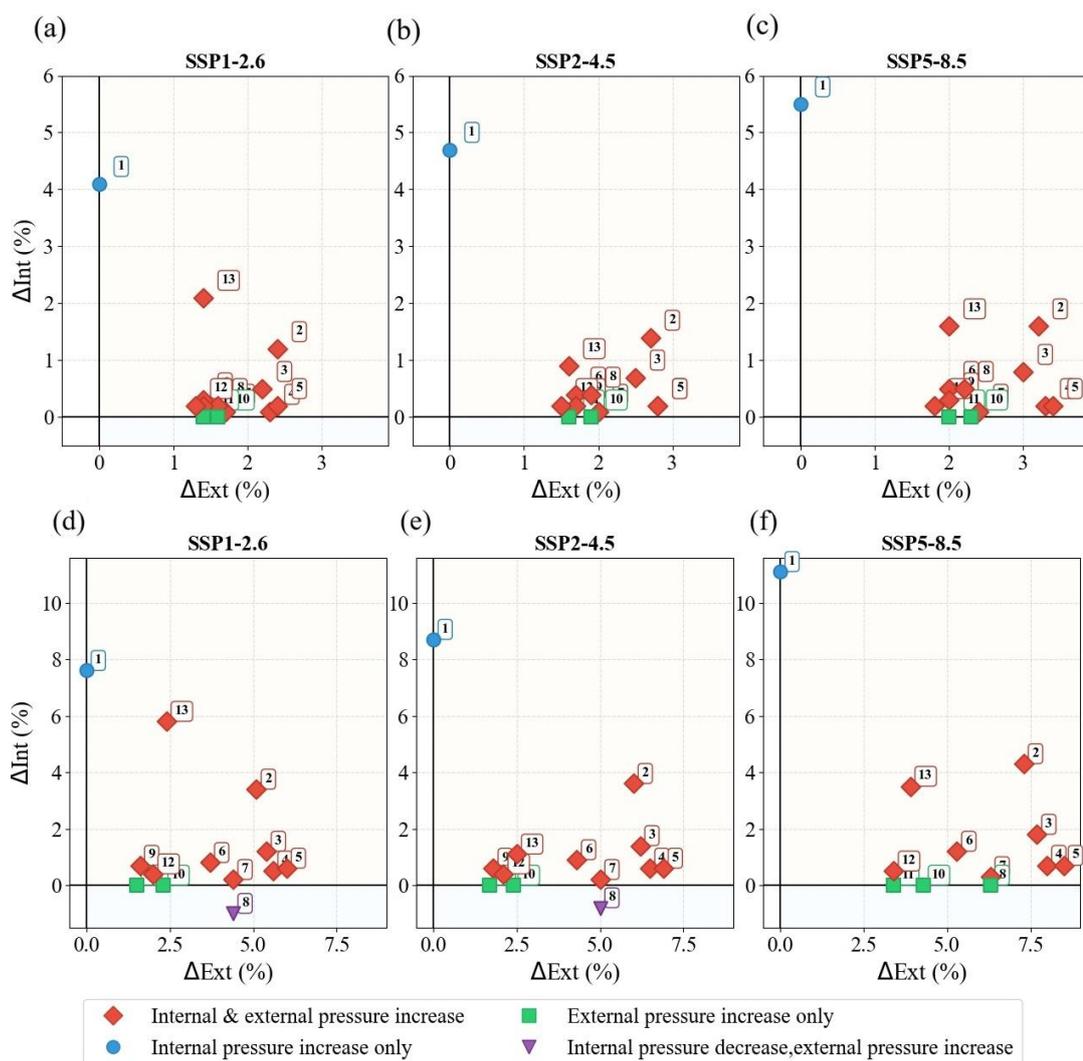
3.2.3 Changes in internal and external irrigation pressure across subregions

Under future climate scenarios (2021–2040), both internal and external irrigation pressure in the basin exhibit an overall increasing trend at the annual scale (Figure 8a-c). However, the trajectories of change vary markedly among subregions, accompanied by a reordering of pressure growth rates. Relative to the historical periods, the growth rate of external irrigation pressure in the future slightly decreases in the downstream subregions (9–13), while it continues to intensify in the upper- and midstream subregions (2–8). Specifically, compared to 1980–2000, external pressure of 2001–2020 in Subregions 2–8 increased at an average annual rate of 1.3%. Compared to 2001–2020, 2021–2040 rise to 2.4% under future scenarios. By contrast, Subregions 9–13 experienced a higher historical increase of 2.2%, which moderates to 1.7% in the future. For internal irrigation pressure, growth slows only in Subregions 3, 6, 8, 9, 12, and 13, whereas growth rates in Subregions 10–11 remain largely stable.

Under dry-season conditions (Figure 8d-f), most subregions continue to experience increases in both internal and external irrigation pressure under the SSP1–2.6 and SSP2–4.5 scenarios relative to 2001–2020, although the magnitude of these increases is generally smaller than during the historical period. Subregion 8 is the only exception, showing a partial alleviation of internal irrigation pressure due to increased water availability. External irrigation pressure increases most strongly in the upstream subregions (2–5), followed by the midstream subregions (6–8), while the downstream subregions (9–13) exhibit comparatively smaller increases. Considering integrated pressure characteristics, Subregion 13 remains the most irrigation-water-stressed area under future scenarios, driven by its high internal irrigation water withdrawal relative to available water and reduced local availability caused by upstream withdrawal. Under the multi-year mean of the three climate scenarios, internal and external irrigation pressures in Subregion 13 reach approximately 23% and 18%, representing increases of about 3.5% and 3.0% relative to the historical period. This indicates that Subregion 13 is a critical hotspot of basin-scale irrigation



315 water risk and highlights the need for integrated management measures. In terms of pressure growth magnitude, Subregion 2 exhibits the largest combined increase in internal and external pressure, indicating rapidly intensifying compound pressures under future scenarios. A closer examination of internal and external irrigation pressure reveals that Subregion 1 shows the largest increase in internal pressure among all subregions, with an average rise of about 9% across three climate scenarios relative to the historical period. Although located in the uppermost part of the basin and characterized by a relatively small
 320 irrigation extent, low internal water-use efficiency results in disproportionately high local irrigation pressure, highlighting the urgent need for efficiency improvements. By contrast, Subregions 4 and 5 experience the strongest increases in external pressure, reflecting markedly intensified upstream water competition and a growing reliance on basin-scale water allocation and coordination mechanisms.



325 **Figure 8: Internal (ΔInt) and external (ΔExt) irrigation pressure changes under climate change scenarios, relative to 2001–2020, at annual (a–c) and dry-season (d–f) scales.**



3.3 Classification of irrigation pressure system type

Based on the dominant irrigation pressure in each subregion, and through a joint analysis of changes direction in internal and external irrigation pressures, the irrigation pressure system type across the study area is classified into eight typical scenarios (Table 4). This scenario-based classification provides a systematic representation of the evolutionary pathways of different subregions under the combined or counteracting effects of internal and external irrigation pressures, thereby offering a framework for identifying structural differences in regional irrigation water pressure regimes and their underlying response mechanisms.

Table 4: Criteria for classifying irrigation pressure system types

Scenario	Internal pressure change	External pressure change	Dominant pressure	Pressure system types	Description
1	↑	↑	Externally dominated	Externally reinforced accumulative	External withdrawal continues to intensify, while internal pressure rises concurrently. System pressure accumulates rapidly and is primarily driven by external factors.
2	↑	↑	Internally dominated	Internal expansion-dominated	External pressure exists, but internal water-use expansion is faster. System pressure is mainly sourced from internal demand growth.
3	↓	↑	Externally dominated	Internally adaptive	Internal irrigation pressure is alleviated, partially offsetting external withdrawal, but overall pressure remains externally dominated
4	↓	↑	Internally dominated	Reverse-pressure adaptive	Despite rising external withdrawal, internal adjustments play a dominant role in system change.
5	↑	→	Internally dominated	Internally constrained expansion	External water conditions remain stable, while internal water demand continues to increase. System pressure growth is mainly driven by internal expansion.
6	↓	→	Internally dominated	Internally regulated mitigation	External pressure remains stable, while internal water-saving or structural adjustments alleviate system pressure.
7	→	↑	Externally dominated	Externally reinforced	External water withdrawal intensifies, while internal demand remains largely unchanged. System pressure is primarily driven by external environmental changes.
8	→	↓	Externally dominated	Externally improved response	External water conditions improve, and internal demand remains stable. System pressure declines in response to external improvements.

At the annual scale, pronounced spatial heterogeneity is observed in irrigation pressure system types across subregions during the historical period (Table 5). According to the criteria for classifying irrigation pressure system types, Subregion 1 is classified as an internally constrained expansion type, indicating that increasing local irrigation water demand is the primary source of system pressure. Subregions 8 and 13 are characterised by an internal expansion-dominated type, with substantial increases in internal irrigation pressure and system evolution largely governed by rapid growth in local irrigation water withdrawal. Subregions 10 and 11 exhibit an externally reinforced type, in which internal pressure changes are limited while external water resource occupation continues to strengthen. The remaining subregions are generally classified as an externally

reinforced accumulative type, characterised by concurrent increases in both internal and external pressures, with external pressure dominating system evolution.

Annual-scale irrigation pressure system types remain largely stable under future climate scenarios, with a pronounced transition observed only in Subregion 8. Specifically, Subregion 8 shifts from an internal expansion-dominated type during the historical period to an externally reinforced accumulative type under future scenarios. This transition reflects a weakening of internal water withdrawal expansion and a gradual shift in the pressure structure from internal dominance toward external dominance.

At the dry-season scale, irrigation pressure system types in most subregions are consistent with those at the annual scale for both historical and future periods. Subregion 8 again represents an exception. During the historical period, it is characterised by an internal expansion-dominated in the dry season, with rapidly increasing local irrigation water demand serving as the dominant source of pressure. Under future climate scenarios, however, Subregion 8 exhibits a more pronounced and complex evolution of irrigation pressure structure. Under the SSP1–2.6 and SSP2–4.5 scenarios, partial alleviation or stabilisation of internal pressure, combined with continued increases in external pressure, leads to a transition toward an internally adaptive type. In contrast, under the SSP5–8.5 scenario, internal pressure remains largely unchanged while external occupation intensifies markedly, resulting in a further transition to an externally reinforced type. These results indicate that Subregion 8 is highly sensitive to climate scenario differences during the dry season and exhibits strong scenario dependence. This behaviour highlights the complexity and uncertainty of future dry-season water resource risk structures in this subregion.

Table 5: Irrigation pressure system types for each subregion during the historical and future periods

Subregion	History	1-2.6	2-4.5	5-8.5	History	1-2.6	2-4.5	5-8.5
Year					Dry season			
1	Internally constrained expansion							
2-7	Externally reinforced accumulative							
8	Internal expansion-dominated	Externally reinforced accumulative	Externally reinforced accumulative	Externally reinforced accumulative	Internal expansion-dominated	Internally adaptive	Internally adaptive	Externally reinforced
9	Externally reinforced accumulative							
10-11	Externally reinforced							
12	Externally reinforced accumulative							
13	Internal expansion-dominated							



360 4 Discussion

4.1 Comparison with previous studies

Downstream subregions experience markedly higher irrigation pressure than upstream areas, particularly during the dry season. These findings are consistent with previous studies on the impacts of irrigation water use in transboundary rivers. Several studies have shown that upstream irrigation expansion can significantly exacerbate water pressure in downstream agricultural systems of the Mekong River by altering river flow and its seasonal distribution (Hoang et al., 2019; Munia et al., 365 2016). Traditional studies often attribute downstream water pressure directly to increased upstream withdrawal or climate-driven runoff reductions, overlooking the amplifying or buffering role of local water use. In contrast, this study explicitly distinguishes between internally driven water-use expansion and externally imposed upstream pressure. This distinction enables a clearer identification of subregions where pressures can be mitigated through local management and those that require transboundary coordination, thereby providing a more nuanced characterization of basin-wide irrigation water-use structures. 370 The results show that even when overall water availability does not change dramatically, different subregions may follow markedly different pressure evolution pathways due to variations in internal irrigation water-use patterns. At both annual and dry-season scales, during the historical period, Subregions 1, 8, and 13 were dominated by internal pressure, while the remaining subregions were primarily dominated by external pressure. Under future climate scenarios, Subregion 8 shifts from being internally dominated to externally dominated, whereas the dominant pressure in the other subregions remain unchanged. 375 Furthermore, the transition of Subregion 8 from internal to external pressure dominance under future scenarios reflects the non-stationarity and path dependence of pressure-driving mechanisms in transboundary river basins.

In addition, the results of this study are compared with findings from other typical transboundary river basins. Previous studies have shown that during the dry season, upstream surface water demand in the Indus River continues to increase, in 380 some sub-basins even exceeding the available water at the same time (Smolenaars et al., 2021). This creates pronounced spatiotemporal hotspots of water pressure in the downstream areas. In these hotspot regions, seasonal water availability is reduced by more than 25% relative to natural conditions, significantly affecting the sharp decline in per capita seasonal water availability downstream in the future. Consequently, the continued increase in upstream water withdrawal may trigger local water shortages and is increasingly recognized as a major driver of downstream water pressure during the dry season. In the Zambezi River Basin, consumptive water use such as irrigation currently accounts for approximately 15–20% of available 385 water and is projected to increase to around 40% by 2025 under existing development planning scenarios, indicating a significant growth trend in water use (Beck, 2010). In the absence of effective international water allocation cooperation, the combination of population and economic growth with expanding irrigated agriculture may have substantial impacts on basin runoff processes and transboundary water distribution. Compared with the aforementioned studies, the scenario simulations in this study suggest that under the SSP5–8.5 scenario in 2040, the annual proportion of irrigation water use relative to available 390 water remains around 19%, which is lower than the high annual water-use levels reported in Zambezi River Basin. However, at the dry-season scale, irrigation water demand could rise to approximately 59% of available water. Under this condition,

upstream irrigation-induced reductions could lower available water in the delta region by about 31% during the dry season under SSP5–8.5 in 2040. This magnitude of reduction is comparable to the dry-season water pressure hotspots identified in the Indus River Basin, indicating that even when annual water-use proportions are relatively moderate, dry-season water risks can be substantially amplified and should not be overlooked.

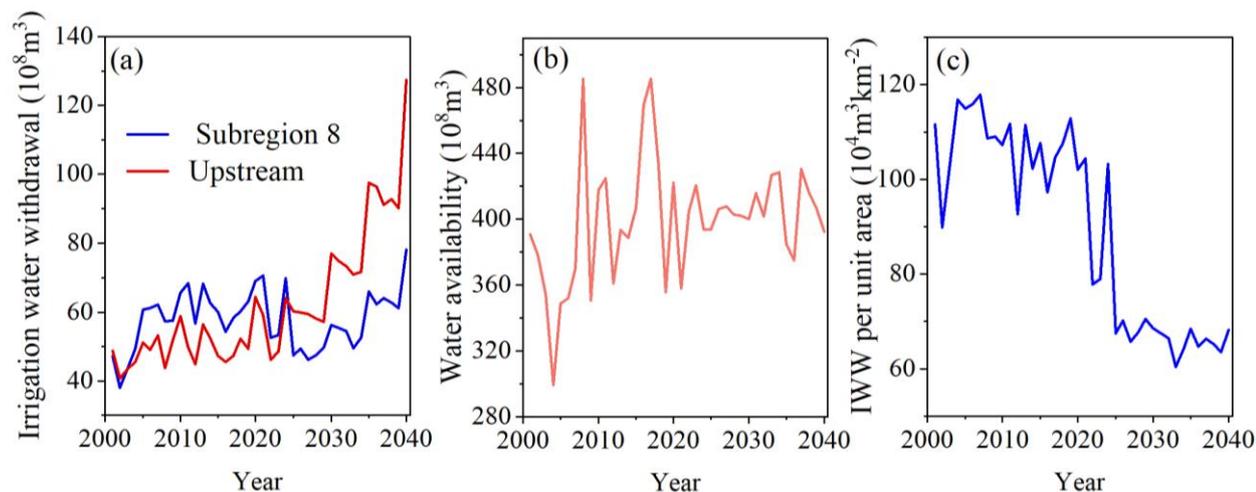
4.2 Mechanisms underlying the dominance patterns of internal and external irrigation pressure

Climate change increases river flows in the Mekong Basin, which may affect downstream water availability, but it does not directly mitigate the impact of upstream irrigation expansion on downstream water pressure (Hoang et al., 2016). Under future climate scenarios, the dominant water pressure type in Subregion 8 shifts from internal to external pressure, indicating a substantial structural change in the local water resource constraint mechanisms. This transition is not driven by a sole increase in internal water-use pressure, but rather results from the continued intensification of external pressure, both in magnitude and relative contribution.

Specifically, although local irrigation water withdrawal in Subregion 8 continues to increase under future scenarios, its growth rate is clearly lower than the rate of upstream irrigation expansion (Figure 9a). From 2025 onward, upstream irrigation withdrawal exceed the local water use in Subregion 8, representing a critical turning point in which the primary source of water pressure shifts from being internally dominated to externally dominated.

Although future dry-season water availability is projected to increase slightly under climate change, upstream irrigation withdrawal is expected to grow much faster. Specifically, during 2001–2020, the multi-year average dry-season irrigation water withdrawal in the upstream region was approximately $5.0 \times 10^9 \text{ m}^3$, increasing to about $7.4 \times 10^9 \text{ m}^3$ in 2021–2040, a rise of 48% (Figure 9a). In contrast, the dry-season available water to Subregion 8 increased only modestly from about $39.4 \times 10^9 \text{ m}^3$ to $40.6 \times 10^9 \text{ m}^3$ (Figure 9b), an increase of roughly 3%. This asymmetry between demand and supply may be partially smoothed at the annual scale by increased runoff, but it is especially pronounced during the dry season, accelerating the structural shift in Subregion 8's dominant water pressure from internal to external sources.

Meanwhile, analysis based on irrigation water withdrawal per unit area shows a significant decline in water withdrawal intensity in Subregion 8 after 2025. Prior to 2025, the multi-year average irrigation water withdrawal per unit area was approximately $1.05 \times 10^6 \text{ m}^3 \text{ km}^{-2}$, dropping to about $0.67 \times 10^6 \text{ m}^3 \text{ km}^{-2}$ after 2026, indicating an improvement in local water-use efficiency (Figure 9c). Therefore, the transition in the dominant internal and external irrigation water pressure in Subregion 8 results from the combined effects of continued upstream irrigation expansion, dry-season hydrological responses under climate change, and local irrigation efficiency. This evolution reflects a typical pathway of irrigation water pressure transformation for downstream areas in transboundary river basins under future climate scenarios. Even when annual-scale conditions appear relatively moderate, external irrigation during the dry season may gradually become the dominant constraint.



425 **Figure 9: Dry-season irrigation characteristics in Subregion 8: local and upstream irrigation withdrawal (a), water availability (b), and irrigation withdrawal (IWW) intensity (c)**

5 Conclusions

This study employs the “Pressure–State–Response (PSR)” analytical framework to systematically assess the spatial patterns and evolution of water pressure in the Lancang–Mekong Basin under the combined influences of irrigation water withdrawal and climate change. The results indicate that during the historical period, Subregions 1 (within China), 8 (mainly in Thailand), and 13 (mainly in Vietnam) were clearly dominated by internal irrigation pressure, with the proportion of local irrigation water use substantially exceeding the impact of upstream withdrawal. The remaining subregions were primarily influenced by upstream irrigation-induced pressure. Under future climate scenarios (2021–2040), both internal and external pressures across the basin exhibit an overall increasing trend and display pronounced nonlinear evolution and spatial heterogeneity. Compared with the historical periods (1980–2000 and 2001–2020), the growth rate of external irrigation pressure in downstream subregions (9–13) tends to slow, whereas the mid- and upper-stream subregions (2–8) continue to experience an increasing trend.

Subregion 8 is projected to undergo a structural shift in its dominant water pressure under future scenarios and exhibits multi-pathway evolution depending on the climate scenario. Under SSP1–2.6 and SSP2–4.5, internal pressure tends to stabilize while external pressure continues to rise, resulting in a transition from an internal expansion-dominated type to an internally adaptive type. In contrast, under SSP5–8.5, external withdrawal pressure intensifies markedly, driving further evolution toward an externally reinforced type. By comparison, Subregions 13 and 9 consistently remain internally expansion-dominated and externally reinforced accumulative type, respectively, under both historical and future scenarios, indicating persistent structural vulnerability in these areas.

Based on the above findings, it is recommended that upstream regions prioritize alleviating water-use competition and continue improving irrigation water-use efficiency. Compound high-pressure areas in the mid- and lower basin (e.g., Subregion

13) require coordinated management of internal demand alongside mitigation of external pressures. In contrast, externally dominated regions must rely on effective transboundary basin coordination mechanisms to reduce the spatial propagation of competitive water use. The source-based subregion identification approach proposed in this study provides a quantitative tool for diagnosing water pressure in transboundary basins and offers a scientific basis for the equitable allocation of water governance responsibilities, thereby supporting more objective decision-making for negotiated water resources management.

Code and data availability. Hydrological data are accessible at <https://portal.mrcmekong.org/home> (last access: 22 January 2026). Code for extracting canals across the lower Mekong can be obtained upon reasonable request from the primary author of the paper.

Author contributions: FT conceptualized and designed the study. HZ contributed to model development, data analysis, and manuscript writing. ZZ contributed to revising the manuscript. All authors participated in discussions throughout the study, provided critical feedback, and approved the final version of the manuscript.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Hydrology and Earth System Sciences.

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