

Article

River–Canal Changes in the Middle Reaches of the Minjiang River (1644–1949): Spatiotemporal Evolution and Driving Mechanisms

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Abstract

The middle reaches of the Minjiang River, shaped by the Dujiangyan irrigation system, provide a typical setting for studying long-term human–water interactions. During the Little Ice Age, the water management system as a whole experienced a full cycle of recovery, expansion, and decline from 1644 to 1949 (Qing to Republican period), although subregions exhibited marked spatial heterogeneity. This heterogeneity makes the area an ideal case for comparative analysis; however, previous studies have neither quantitatively reconstructed river–canal changes nor systematically disentangled the composite natural and anthropogenic drivers across different subregions. Using archival documents, historical maps, remote sensing imagery, and water cultural heritage sites, this study reconstructs the evolution and quantifies two change types: anthropogenic construction, including new construction, reconstruction, and modification, and environmentally driven changes such as rerouting, damage, and maintenance. Correlations were analyzed among the four subregions: Inner River, Outer River, Nanhe River, and the Lower Basin to identify driving mechanisms. Results indicate that anthropogenic construction is constrained by natural conditions and driven by population growth, whereas environmentally driven changes are primarily caused by floods and worsened by canal head maintenance failure. The four spatially differentiated driving patterns are: Inner River—human-dominated intervention type; Outer River—flood stress type; Nanhe River—low-disturbance stable type; and Lower Basin—natural–human composite type. This study offers new insights into long-term human–water interactions in large irrigation districts under climate change.

Keywords: river–canal change intensity; driving mechanisms; Dujiangyan; little ice age; middle reaches of the Minjiang river

Academic Editor: Chin H Wu

Received: 15 May 2026

Revised: 21 June 2026

Accepted: 25 June 2026

Published: 27 June 2026

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1. Introduction

Since the mid-15th century, the world experienced the Little Ice Age, which peaked during the Ming and Qing periods in China and was marked by cooler temperatures and frequent droughts and floods [1]. Historical records such as the Mingshi and Qingshigao document numerous extreme weather events that caused widespread damage to agriculture and society [2]. Climate fluctuations not only directly affected river hydrology,

morphology, and distribution, but also indirectly shaped the basin environment by altering human water use [3].

The middle reaches of the Minjiang River contain the Dujiangyan irrigation system, a world-famous irrigation project that has operated continuously for over 2200 years [4]. Its “4:6 water diversion” mechanism integrates water regulation and allocation, and its adaptive management system has shaped the regional water environment [4,5]. Between 1644 and 1949 (Qing to Republican period), the basin underwent the full cycle of water system recovery, development, and decline under the Little Ice Age climate, creating a sequence of water environment changes where natural processes and human interventions were closely intertwined. A systematic analysis of river and canal changes and their driving mechanisms during this period provides a valuable case for understanding how human engineering and natural river systems co-evolve over the long term in response to climate change.

In the Minjiang basin, the Little Ice Age was characterized by pronounced cold phases and increased climate variability, with the 19th–20th centuries identified as a period of notable temperature fluctuations in western Sichuan [6]. This climatic instability was accompanied by altered precipitation patterns and heightened drought–flood frequency [7], providing the broader environmental context for examining long-term river–canal changes and their driving mechanisms.

Existing research has made notable progress. Studies on water conservancy in the middle reaches of the Minjiang River have focused on engineering technology (e.g., the evolution of headworks) [8,9], management institutions [10], and cultural values [11]. In historical hydrology, Chinese scholars pioneered the quantification of drought and flood severity based on historical documents [12], converting qualitative disaster records into standardized, comparable parameters. This approach has been widely applied and refined in subsequent studies [13–15], providing guidance for using historical documents in paleohydrological research. Regarding spatial river evolution, the widespread use of GIS has allowed researchers to integrate historical maps and remote sensing imagery [16–19]. This approach no longer treats the basin solely as a natural system but instead examines human–hydrology interactions across multiple scales and factors [20–24].

Nevertheless, significant gaps remain. First, most studies adopt a homogeneous basin perspective or rely solely on natural geographic divisions, overlooking that sub-basins within a large irrigation district may exhibit fundamentally different water environment evolution patterns due to functional positioning and human intervention. Second, comprehensive studies on multiple factors driving river–canal changes are limited: previous research mainly focuses on technical or institutional dimensions, lacking a unified framework integrating natural and anthropogenic drivers. Third, quantitative assessment and coupling analysis remain insufficient, and the quantitative evaluation of historical river–canal change intensity is not fully developed, limiting reliable comparisons across periods and regions.

Therefore, this study focuses on the middle reaches of the Minjiang River from 1644 to 1949 with the following objectives: (1) to reconstruct the spatiotemporal evolution of river channels and water system distribution; (2) to quantify the intensity of two types of canal changes—anthropogenic construction (including new construction, reconstruction, and modification) and environmentally driven changes (including rerouting, damage, maintenance); and (3) to quantitatively reveal the compound driving mechanisms of river–canal changes using multiple natural and anthropogenic factors, and identify differences in driving patterns across four subregions (Inner River, Outer River, Nanhe River, and Lower Basin).

The results reveal distinct driving patterns in each subregion. In the Inner River, classified as human-dominated intervention, water environment stability depends heavily on

the effective operation of the Dujiangyan irrigation system. The Outer River follows a flood-stress pattern, with floods dominating environmentally driven changes. The Nanhe River exhibits a low-disturbance stable pattern. In the Lower Basin, classified as a natural–human composite pattern, population growth drives water management construction, while water environment stability is largely influenced by upstream hydrological conditions. This study presents a coding and grading method for quantifying river–canal change events from historical documents—a data type not previously quantified in this way—with criteria defined based on canal hierarchy, spatial extent, and the number of channels involved. A multi-factor analytical framework is also established that integrates natural and anthropogenic drivers, enabling subregional comparison and identification of spatially heterogeneous driving patterns. This approach provides a novel perspective for quantitatively analyzing historical human–water interactions and offers insights into sustainable river management under climate change.

2. Study Area

The Minjiang River, a first-order left-bank tributary of the upper Yangtze River, is located in central Sichuan Province. This study focuses on the reach from Guan County (present-day Dujiangyan City) to Leshan (Figure 1), which has a total length of approximately 223 km and a basin area of about 102,000 km². The upper reaches flow through the Chengdu Plain and are relatively straight, whereas the lower reaches enter the hilly central basin, characterized by gentle flow and developed floodplains [25,26].

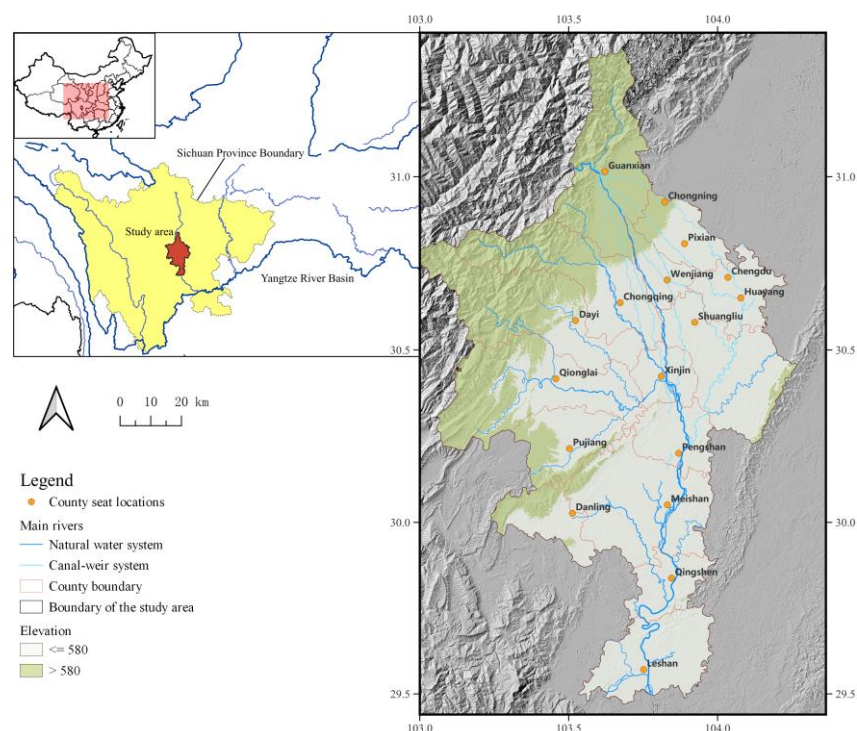


Figure 1. Location map of the middle reaches of the Minjiang River basin.

The study area lies in the transition zone between the eastern Tibetan Plateau and the Sichuan Basin, along the Guanxian–Emei line. To the west lies the Longmenshan fold-and-thrust belt, while to the east are the West Sichuan depression and Central Sichuan uplift. The terrain comprises plains, hills, and low mountains, underlain by Jurassic–Cretaceous red-bed sandstones and mudstones, and Quaternary alluvial–proluvial deposits, with multiple river terraces developed along the Minjiang River [25,26]. Based on water supply conditions, hydraulic control, confluence nodes, and administrative divisions

during the Qing to Republican period, the study area is divided into four subregions: the Inner River, Outer River, Nanhe River, and the Lower Basin. The canal head serves as the hydrological control core for the entire basin (see Table 1 and Figure 2 for details). The Inner and Outer River subregions are located on the Chengdu Plain, dominated by the Minjiang alluvial fan and are characterized by deep and fertile soils, wide and low banks, and extensive contiguous farmland. The Nanhe River subregion, situated in the southwestern part of the Chengdu Plain, represents a transition from low mountains to plains, with soils composed of mixed yellow earth and alluvial deposits, which are heavy and acidic. The Lower Basin subregion is located in the hilly downstream area of the basin and has relatively poor soil quality.

Table 1. Four subregions and the Dujiangyan canal head in the middle reaches of the Minjiang River.

Research Unit	Administered Counties and Districts	Division Rationale & Hydrological Features
Canal Head	Guan County	Core of the Dujiangyan water control system; the Fish Mouth Levee (<i>yuzui</i>) diverts the Minjiang mainstream, regulating water distribution across the entire basin through the ‘4:6 water diversion’ mechanism, serving as the main hydraulic control point [26,27].
Inner River	Chengdu, Huayang, Chongning, Pixian,	Water supply fully relies on the Minjiang mainstream regulated at Baopingkou; forms an artificial water network with high irrigation reliability and is strongly influenced by engineering operations [26].
Outer River	Wenjiang, Shuangliu, Chongqing, Xinjin	Receives natural inflow and floodwater from the Minjiang main channel (Jinma River); functions primarily for flood drainage and sediment transport; faces relatively high flood risk [26].
Nanhe River	Dayi, Qionglai, Pujiang	A first-order tributary of the Minjiang; water supply mainly from western mountain streams in the upper Nanhe; weakly regulated by Dujiangyan; runoff depends largely on local precipitation [28].
Lower Reach	Pengshan, Meishan, Danling, Qingshen, Leshan	After the confluence at Pengshan–Jiankou, a single main channel is formed. The reach is backwatered by the Dadu River and Qingyi River, resulting in a gentle channel slope and making it a key flood-prone area in the basin [29].

Notes: Due to the rerouting of the Jiang’an River to draw water from the Inner River, Wenjiang and Shuangliu have belonged to the Inner River since the 1950s, but they belonged to the Outer River during the study period (1644–1949).

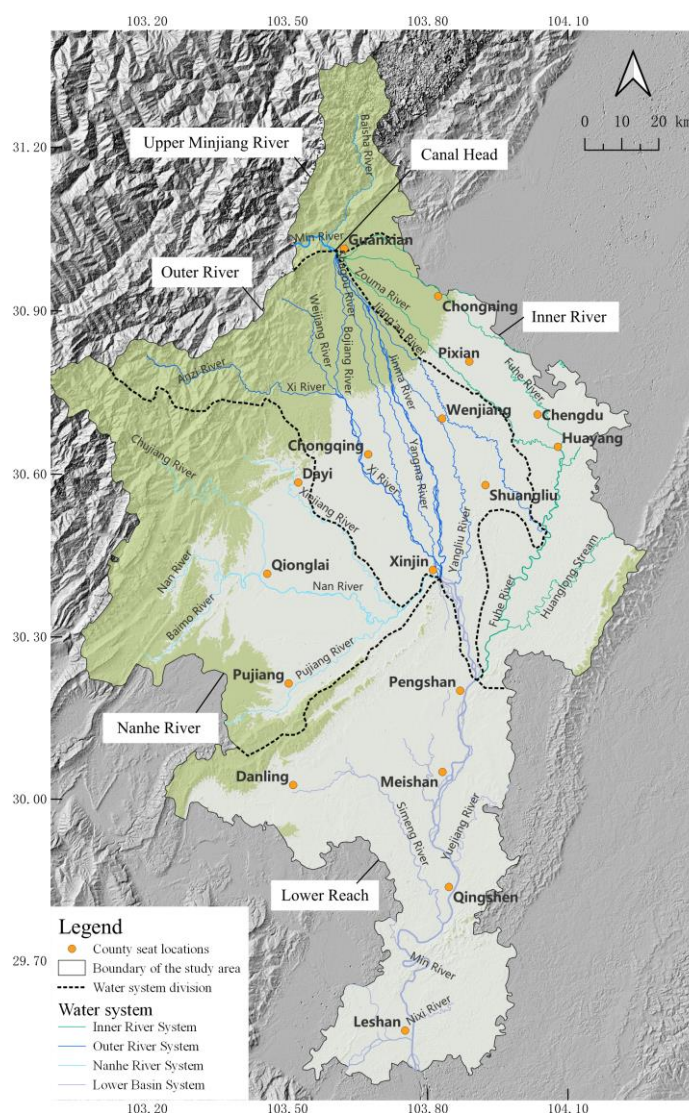


Figure 2. Subdivision of the Middle Reaches of the Minjiang River Basin.

The middle reaches of the Minjiang River experience a humid subtropical monsoon climate with distinct seasons. Rainfall is concentrated between June and September, and the main flood season lasts from July to October. Droughts and floods occur frequently. Floods are typically triggered by heavy rainfall and are characterized by high peaks and large volumes, whereas spring droughts are the most common and often follow winter dry periods [25].

The basin has a long history of water management. The Dujiangyan canal head, constructed in 256 BCE, comprises the Fish Mouth Levee, Flying Sand Weir (feishayan), and Baopingkou. Using the ‘4:6 water diversion’ mechanism, water is regulated and distributed through a five-level canal network (main, branch, paddy, field, and farm), forming an integrated system of artificial and natural canals and weirs [4,5,30]. Wars during the late Ming and early Qing periods caused severe damage, but coordinated efforts by officials and local communities from early Qing to the Qianlong reign restored and expanded irrigation to levels equal to or higher than before [4,25,26]. This system effectively reduced flood risks, improved regional climate and soil conditions, and contributed to the formation of the local hydrological environment [5].

3. Materials and Methods

3.1. Data Sources and Processing

This study utilized six categories of data (Table 2). All spatial data were processed using ArcGIS 10.8 and QGIS 3.16. The CGCS2000 national geodetic coordinate system and Gauss projection were consistently applied to ensure spatial consistency across all datasets.

Table 2. Data sources, processing, and applications.

Data Type	Specific Data/Content	Time Range	Processing	Purpose
Historical maps	Kangxi “Complete View of Imperial Domains,” Sichuan sheets	1708–1717	Study area clipping	Control of macro water system patterns
	Prefecture- and county-level administrative maps, and water conservancy maps	Qing–Republic	Data stitching, area clipping	Identify river start/end points, hierarchical relationships
Republican topographic maps	1:50,000 (20 sheets)	1939–1948	Georeferencing using ArcGIS 10.8	Reconstruct 1940s high-precision water system distribution
	1:100,000 full area	1927–1934		
	Historical water conservancy maps (e.g., the four maps, including “Complete Map of Dujiangyan Dikes and Canals”)	1933–1946		
Remote sensing	Esri World Imagery (<1 m resolution)	2024		Planar control reference used for georeferencing and geometric correction
	Sentinel-2 Level 1C TOA (cloud <1%)	2023–2024	Band combination (11,8,3) → geometric correction → DOM	Extraction of the current river network and interpretation of ancient channels
historical documents and records	63 primary sources (geography, water conservancy, local gazetteers)	Qing–Republic	Extract river/canal, drought/flood, site information (see Sections 3.2.1 and 3.4.2)	Build river–canal change database; reconstruct drought/flood spatiotemporal distribution; site localization and dating
	11 contemporary compilations of climate and water conservancy data	Modern		
Water cultural sites	383 sites	Qing–Republic	Cross-validate spatial coordinates and initial construction dates	Channel spatial calibration, chronological constraint
Basic geographic data	ASTER GDEM V3	Modern	Study area clipping, DEM pit filling, flow direction analysis	Terrain correction
	Modern county-level administrative points/boundaries; CHGIS 1911 county-level points/boundaries	Modern/1911	Study area clipping	Administrative alignment

All map data, including 1:50,000 and 1:100,000 Republican topographic maps, remote sensing imagery, and basic geographic data, underwent geometric correction and spatial registration. The average root-mean-square error (RMSE) for the georeferenced 1:50,000 maps was 23.8 m (0.48 mm on the map), within the accuracy range of 0.50–0.75 mm defined by the modern topographic map standard (GB 12343-1990). The 1:100,000 maps had an average RMSE of 79.0 m (0.79 mm), which meets the 500 m error control threshold

reported in comparable studies [31–34]. Sentinel-2 imagery was geometrically corrected using Esri World Imagery for planar control and ASTER GDEM for elevation control, with planar errors controlled within one pixel (10 m). Historical documents and records (Table S1) were organized into thematic databases covering river–canal changes, drought–flood distribution, and water cultural heritage sites. The spatial coordinates and construction dates of 383 water cultural heritage sites were cross-validated using field surveys, literature sources, historical maps, and satellite imagery before being incorporated into the database.

3.2. Historical Water System Reconstruction Methods

3.2.1. Extraction of River–Canal Information

Based on historical documents, river–canal change events were recorded for four periods: Early Qing (1644–1735), Mid-Qing (1736–1820), Late Qing (1821–1911), and Republican (1912–1949), across five units: the Dujiangyan canal head, Inner River, Outer River, Nanhe River, and Lower Basin. Each change was classified into one of six types: new construction, reconstruction, modification, rerouting, maintenance, or damage, with the remaining five types applying to artificial canals and weirs. Rerouting refers to natural or artificial channels changing course due to cycles of erosion, transport, and deposition[35], primarily triggered by floods in the study area. New construction denotes newly built dikes or canals. Reconstruction involves rebuilding abandoned or damaged channels in situ or in nearby locations. Modification refers to alterations of water intakes or channels to improve inflow, caused by canal expansion or sedimentation from floods, as exemplified by Mayi Weir and Qifen Weir [36,37]. Maintenance indicates regular periodic repairs. Repair refers to short-term localized restoration. Damage indicates long-term disuse or structural failure. All change records are provided in Supplementary Table S2.

3.2.2. River and Canal Classification

Vector data of the river network were extracted from georeferenced Republican topographic maps. To distinguish natural rivers from artificial canals and weirs, separate classification rules were applied and subsequently integrated into a unified grading system (Table 3).

Table 3. Correspondence of natural stream order and artificial canal levels.

Natural Stream Order (This Study)	Corresponding Strahler Order	Canal Level	Definition and Confluence/Water Diversion Rules
0 (Minjiang mainstream)	5	—	Highest-level mainstream; receives stream order 1; canal level A diverts water from this level
1	4	A	Stream order 1 flows into order 0; canal level A diverts water from order 0
2	3	B	Stream order 2 flows into order 1; canal level B diverts water from order 1 or level A
3	2	C	Stream order 3 flows into order 2; canal level C diverts water from order 2 or level B
4	1	D	Stream order 4 flows into order 3; canal level D diverts water from order 3 or level C

1. Natural river classification

The natural river network of the basin exhibits a typical dendritic pattern. The Strahler method [38] was used to classify natural rivers into five orders, which were then converted to a 0–4 scale to ensure consistency with the canal grading system, with 0

representing the Minjiang mainstream. The correspondence between the two systems is provided in Table 3.

2. Canal and weir classification

Canal grading followed standards for agricultural irrigation and drainage systems [30]: channels drawing directly from the Minjiang mainstream (order 0) were assigned grade A; channels fed from order 1 rivers or A-grade channels were assigned grade B; the scheme continued sequentially down to grade D for field-level structures. When a channel branched into two, the larger-flow branch retained the original grade, while the smaller-flow branch was downgraded by one grade. At confluences, the merged channel assumed the higher grade of the two incoming channels.

Hierarchical relationships were primarily determined from historical records: a channel explicitly fed from a river was assigned one order lower (e.g., “diverted from ... river,” “branching from ... river”); channels splitting to a weir retained the same grade if the record indicated “water diverted from ... river to ... weir for a certain distance”; if only a diversion point was mentioned without downstream continuity, the structure was classified as a field-level canal (grade D).

3. Integrated classification system

By combining the natural river classification and canal grading rules, nine hierarchical river-canal levels were established in this study. The names, correspondences, and descriptions of each level are summarized in Table 3.

3.2.3. Reconstruction of Water System Distribution

The water system distribution in the 1940s (Republican era) was reconstructed from 1:50,000 and 1:100,000 topographic maps, supplemented by county gazetteers, water conservancy maps, and other survey materials. Channels were geolocated and named based on documented river–canal names, start and end points, and geographical landmarks such as ferries and temples. For river segments without explicit labels, names were assigned using nearby landmarks and verified against historical records. In the reconstructed 1940s map, all channels of orders 0–3 (or grade C) were named, and some channels of order 4 (or grade D) were also assigned names. Based on these reconstructions and the river–canal change records in Supplementary Table S2, the spatial distribution of rivers and canals was inferred for the Early Qing (up to 1735), Mid-Qing (up to 1820), and Late Qing (up to 1911) periods.

3.3. Quantification of Canal Change Intensity

Due to substantial differences in the scale of river–canal change events recorded in Supplementary Table S2, a grading scheme was developed specifically for river–canal change events, drawing on the general principles of quantifying historical documentary records [12,39]. For example, small D-level farm canals such as Huanglian Weir and Dongjia Weir were assigned to the lower end of the scale. Large B-level irrigation canals like Tongji Weir, which span Pengshan and Meishan counties, irrigate over 68,000 mu and include dozens of branch channels. These canals represent the upper end of the scale. Each change was assigned to one of three levels: level 1 (small-scale), level 2 (medium-scale), and level 3 (large-scale). Detailed grading criteria are provided in Table 4.

Table 4. Grading of river–canal change events in the basin.

Scale	Level	Criteria	Examples
Small	1	Changes in a single 4/D-level canal, or local changes in 1/A, 2/B, or 3/C-level canals, including reconstruction, modification of the	“Dredging of Dujiangyan Li Dui” (A-level canal); “Repair of Inner River Zouma River Xian Nong Dike, over 200 zhang” (B-level canal); “Reopening of

		weir head, partial rerouting, short-term restoration, or damage.	Niutou Weir head" (C-level canal); "Yongdun and Hao Weir constructed in the Xianfeng period of Qing" (D-level canal)
Medium	2	New construction, reconstruction, restoration, or damage of several 4/D-level or 3/C-level canals; partial rerouting, restoration, or damage of multiple 2/B-level canals.	"Outer River flood, Blackstone and Yangma rivers inundated, many dikes in Chong and Guan damaged" (B-level canals); "Repair of the Great Weir, known as Jianggong Weir" (C-level canal)
Large	3	New construction, reconstruction, rerouting, restoration, or damage of 2/B-level or higher canals, multiple 3/C-level canals, or dozens of 4/D-level canals.	"Floods destroyed tens of thousands of acres; Outer River basin severely damaged, provincial government ordered restoration"; "Expansion of Tongji Weir, restoration of 28 ancient canals in Pengshan and 14 in Meishan" (B-level canals)

In this study, the scale of each river–canal change was represented by a weighted value combining the frequency of events and their assigned scale level. The annual mean value of change within a given period is defined as the river–canal change intensity, denoted as q , calculated as follows:

$$q = \frac{3n_3 + 2n_2 + n_1}{N} \quad (1)$$

where n_1 to n_3 represent the number of changes in levels 1 to 3 within the period, and N is the total number of years in that period.

Notes: Equation (1) does not apply normalization by county count, area, or canal segment count, as canal density varies substantially among subregions, and the number of identifiable canal segments changes over time. Introducing a hierarchical canal-based denominator would also require a justifiable correspondence between canal level and event magnitude, which is difficult to establish in practice. Caution is therefore required when interpreting cross-subregional absolute intensity comparisons. To address this limitation, we present both overall correlation analysis ($n = 16$) and the within-subregion temporal trend analysis ($n = 4$ per subregion) to cross-validate the identification of driving mechanisms.

Based on the nature of the changes, new constructions, reconstructions, and modifications were classified as anthropogenic construction changes, referring to active human interventions aimed at improving livelihoods or responding to local policies. Rerouting, damage, and short-term restoration were classified as environmentally driven changes, referring to modifications directly triggered by natural factors such as droughts and floods, which induce passive human responses. This classification facilitates subsequent analysis and discussion.

3.4. Driver Variables and Analytical Methods

Data for the driver mechanism analysis were organized by four study periods: Early Qing (1644–1735), Mid-Qing (1736–1820), Late Qing (1820–1911), and Republican (1912–1949), and four major river subregions: Inner River, Outer River, Nanhe River, and the Lower Basin. Each subregion thus corresponds to four temporal datasets. To eliminate the influence of differing units, all independent and dependent variables were standardized to the [0,1] interval using min–max normalization to ensure comparability.

3.4.1. Dependent Variables

Based on the river–canal change classifications described above, two dependent variables were defined. First, anthropogenic construction change intensity (Y1) quantifies river–canal changes resulting from active human interventions, including new construction, reconstruction, and modification of canals and weirs. Second, environmentally driven change intensity (Y2) quantifies changes caused by natural factors, such as

rerouting, damage, or short-term restoration, which induce passive human responses. After standardization, higher values indicate greater intensity of river–canal changes.

3.4.2. Independent Variables

To explore the drivers of water environment changes, seven independent variables were selected from both natural and human dimensions.

- Drought–Flood Grading

Drought and flood events were extracted from county records in local gazetteers covering the Qing to Republican period, including descriptions such as “major flood,” “severe drought,” or “famine.” Only events attributed to natural meteorological causes were retained, while anthropogenic factors (e.g., levee breaches due to poor maintenance) and politically exaggerated records were excluded. A five-level grading system was applied (1 = flood, 2 = moderate flood, 3 = normal, 4 = moderate drought, 5 = drought), with each event classified according to its textual description (grading criteria and examples are provided in Table A1). For each year, the most severe recorded event was selected, with priority given to summer events. County records with gaps of three to five years were considered as normal events (grade 3), while gaps exceeding five years were excluded. When multiple events occurred in the same year and county, the highest grade was retained.

- Drought Factor (X1) and Flood Factor (X2)

The drought factor (X1) and flood factor (X2) were defined as the indices representing drought and flood intensity, respectively, calculated as weighted sums of the event frequencies across different severity levels within each region and period:

$$I = \frac{2C2 + C1}{Count} \quad (2)$$

where $C2$ is the number of severe events (level 5 for drought, level 1 for flood), $C1$ represents the number of moderate events (level 4 for drought, level 2 for flood), and $Count$ denotes the total number of events. Higher standardized values of X1 and X2 indicate stronger drought and flood intensity.

- Wet–Dry Factor (X3)

Previous studies have shown that wet–dry fluctuations significantly influence water environment changes [40–42]. The wet–dry factor was used to represent interannual variability in basin moisture conditions. First, an annual wet–dry index was calculated for the basin using a weighted approach:

$$I = \frac{5n5 + 4n4 + 3(N - n1 - n2 - n4 - n5) + 2n2 + n1}{N} \quad (3)$$

where $n1$ to $n5$ denote the number of counties at drought–flood levels 1 to 5, and $N = 17$ is the total number of counties in the Qing-era basin. The standard deviation of the wet–dry index within each study period was then calculated as the wet–dry factor (X3). Higher standardized values of X3 indicate greater interannual variability in moisture conditions and a higher likelihood of extreme drought or flood events.

- Temperature Factor (X4)

Temperature fluctuations were quantified using a grading method based on historical climate reconstructions [43–45] and the REACHES database temperature standards [44]. The assignment of X4 values reflects the degree of temperature variability, defined as the frequency and intensity of cold–warm alternations. Graded temperature records were converted to numerical values (0.1–0.9) according to the mapping between warm/cold records and assigned scores (Table 5), and then standardized to the [0,1] interval. Higher standardized X4 values indicate more pronounced temperature variability,

i.e., more frequent and intense alternations between cold and warm extremes, which may amplify hydrological extremes through enhanced climate instability [46].

Table 5. Temperature grading and fluctuation values.

Temperature Grade	Description in Historical Records (Common Expressions in Local Gazetteers and Historical Literature)	Fluctuation Value	Intensity
Level 1 (Extremely Cold)	Extreme winter cold, rivers frozen, plants die, humans and livestock suffer frostbite, extreme cold events occur	0.8–0.9	Very high
Level 2 (Cold)	Cold winters with snow, below-average temperatures, no extreme cold events, only regular cold records	0.6–0.7	High
Level 3 (Normal)	No obvious cold or heat anomalies, stable temperatures, distinct seasons, no extreme events	0.2–0.4	Low
Level 4 (Warm)	Mild winter, little snow, hot summer, early crop maturation, no extreme heat events, only regular warm records	0.5–0.6	High
Level 5 (Extremely Hot)	Extreme summer heat, crops wilt, water shortage, humans and livestock suffer heatstroke, extreme heat events occur	0.8–0.9	Very high

- Population Factor (X5)

The population factor represents the population growth rate of each region within a given period. Historical population data were obtained from archival sources using growth coefficients and interpolation methods (Table 6). The annual growth rate was calculated as:

$$r = \left(\frac{P_t}{P_0} \right)^{\frac{1}{n}} - 1 \quad (4)$$

where P_0 and P_t are the initial and final populations, and n is the interval in years [47]. Higher standardized X5 values indicate faster population growth.

Table 6. Population data sources and acquisition methods.

Period	Year	Data Source	Method of Acquisition
Early Qing	1685	Kangxi <i>Sichuan General Gazetteer</i> , Vol. 30, <i>Population and Tax Records</i> (only prefecture and state totals)	Assumed uniform growth across counties in each prefecture; 1812 data used as baseline, and 1685 populations estimated using growth coefficients [48]
Early Qing	1735	No direct records	Interpolated assuming exponential growth from 1685 to 1812 [48]
Mid-Qing	1812	Jiaqing <i>Sichuan Gazetteer</i> , Vol. 64, <i>Food and Household Population</i> (county totals available)	Directly adopted
Late Qing	1910	Local gazetteers compiled between Guangxu and Xuantong periods (statistical coverage varies)	Adopted directly; male population converted using 4–5 persons per household [47]; outliers adjusted according to regional trends [49]
Republican	1925	1925 <i>Postal Statistics</i>	County populations extracted; reductions due to narrower statistical coverage were adjusted using prior growth rates and concurrent regional growth rates [50]

- Canal Head Control Factor (X6)

The canal head control factor reflects the maintenance intensity of the Dujiangyan canal head. Values were derived from the river–canal change intensity method described above. Canal head repairs may be triggered by flood damage, but also by structural aging, sedimentation, and institutional factors. Thus, higher X6 values indicate greater maintenance requirements, implying reduced hydraulic control efficiency. X6 captures the

overall effectiveness of canal head regulation, jointly influenced by hydrological events and institutional conditions.

- River Network Structure Factor (X7)

The river network structure factor (X7) represents the overall complexity of the river system (Rc), integrating river order distribution and channel length allocation to characterize their combined pattern. Because the network structure changed little during the study period, a fixed value was assigned to each subregion. The relationship between X7 and the dependent variables is considered only in the overall analysis, to reveal how regional differences in river network structure affect river–canal changes. Rc was calculated as:

$$Rc = \frac{N_0}{L / Lm} \quad (5)$$

where N_0 is the number of river orders, L is the total river length (km) in each subregion, and Lm is the total length of the highest-order rivers. Higher standardized X7 values indicate more complete river order distribution, more rational channel length allocation, greater network complexity, and stronger flood retention and mitigation capacity.

Table 7 summarizes all dependent and independent variables, their definitions, and calculation methods.

Table 7. Summary of dependent and independent variables.

Variable Type	Code	Name	Definition	Calculation
Dependent	Y1	Anthropogenic Construction Change	Intensity of new construction, reconstruction, and modification of canals and weirs	Equation (1)
Dependent	Y2	Environmentally Driven Change	Intensity of rerouting, short-term restoration, and damage of rivers and canals	Equation (1)
Independent	X1	Drought Factor	Drought index	Equation (2)
Independent	X2	Flood Factor	Flood index	Equation (2)
Independent	X3	Wet–Dry Factor	Wet–Dry Variability Index	Standard deviation of the wet–dry index calculated using Equation (3)
Independent	X4	Temperature Factor	Temperature Fluctuation Index	Table 5
Independent	X5	Population Factor	Population Growth Rate	Table 6 & Equation (4)
Independent	X6	Canal Head Control Factor	Dujiangyan Canal Head Maintenance Intensity	Equation (1)
Independent	X7	River Network Structure Factor	River Network Complexity	Equation (5)

3.4.3. Analytical Methods

1. Correlation Analysis

Pearson correlation coefficients were calculated to examine linear relationships between dependent variables (Y1, Y2) and natural and human driver factors (X1–X7), in order to assess both the strength and direction of influence. The correlation coefficient is calculated as:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (6)$$

where x_i and y_i are the values of independent and dependent variables, $\bar{x}$ and $\bar{y}$ are their means, and n is the sample size. Significance was set at $\alpha = 0.05$, with $p < 0.05$ indicating a significant correlation and $p \geq 0.05$ indicating non-significance. The coefficient

ranges from -1 to 1 ; $r > 0$ indicates a positive correlation, $r < 0$ indicates a negative correlation, and larger $|r|$ values indicate stronger associations.

2. Regional Comparison Analysis

To reveal spatial heterogeneity in driving mechanisms, correlation coefficients were calculated for each subregion and period. Two types of comparisons were performed:

- (1) Identification of dominant factors: within each subregion, the absolute values of correlation coefficients were compared to identify the primary drivers of river–canal changes;
- (2) Comparison of factor patterns: differences in the relative strengths of natural and human drivers among the four subregions were examined to infer regional patterns of driving mechanisms.

4. Results

4.1. Reconstruction of River–Canal Evolution

The reconstructed river networks of the four subregions from the Qing to Republican period are shown in Figures 3–6, with the overall evolution summarized in Figure 7. Comparison with the Sichuan section of the Kangxi *Huangyu Quanlantu* (Figure A1) indicates that the spatial patterns of the basin's main rivers (orders 0, 1/A, and 2/B) remained largely stable from the Early Qing to the Republican period, with changes occurring primarily in local canals and weirs.

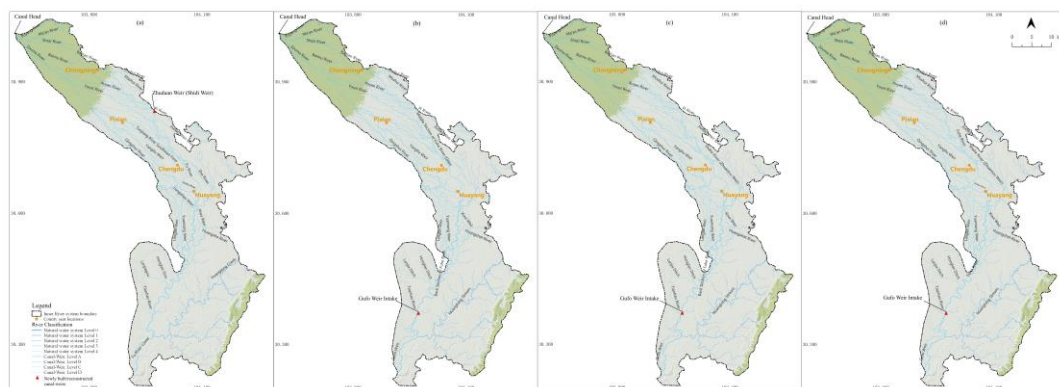


Figure 3. Reconstruction of the Inner River Network from the Qing to Republican period: (a) Early Qing; (b) Mid-Qing; (c) Late Qing; (d) Republican period.

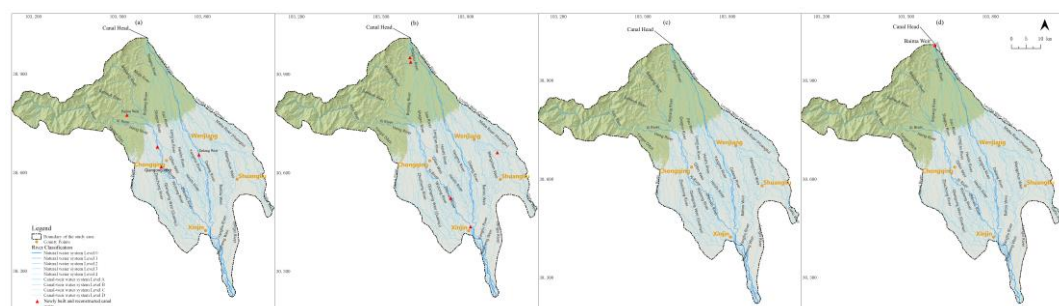


Figure 4. Reconstruction of the Outer River Network from the Qing to Republican period: (a) Early Qing; (b) Mid-Qing; (c) Late Qing; (d) Republican period.

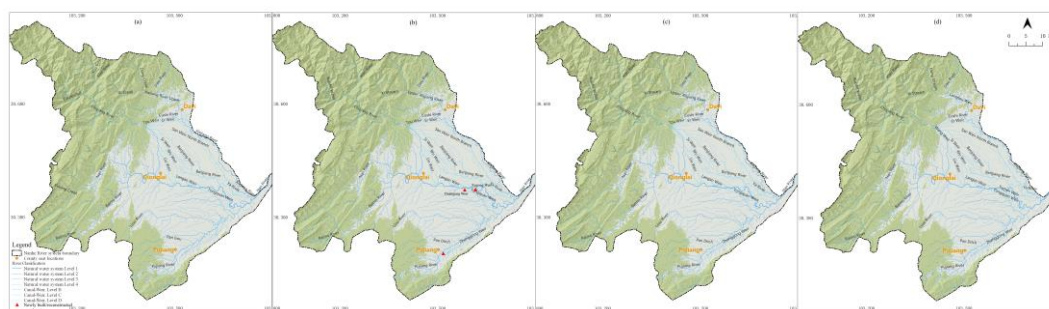


Figure 5. Reconstruction of the Nanhe River Network from the Qing to Republican period: (a) Early Qing; (b) Mid-Qing; (c) Late Qing; (d) Republican period.

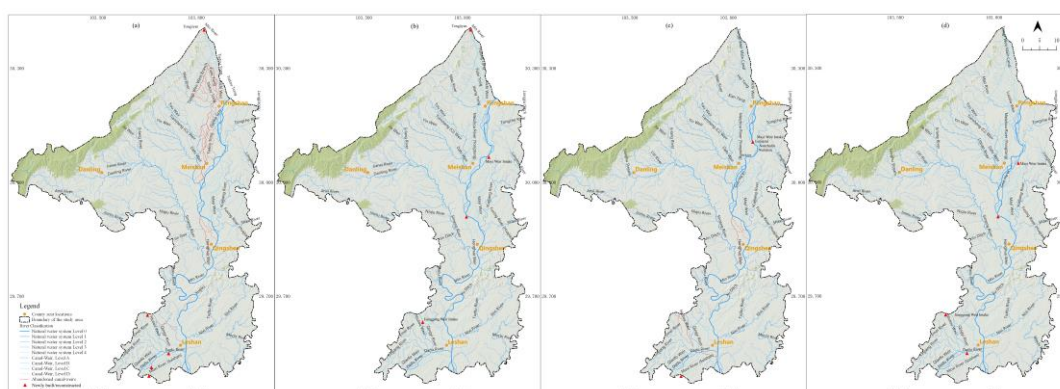
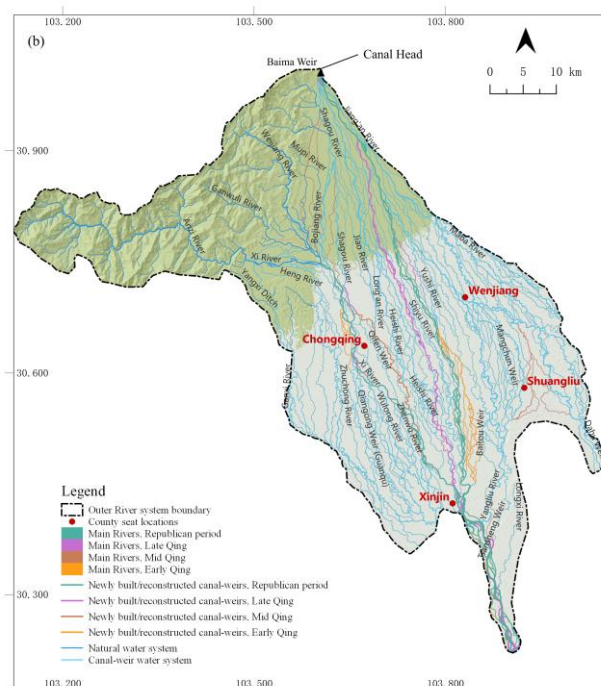
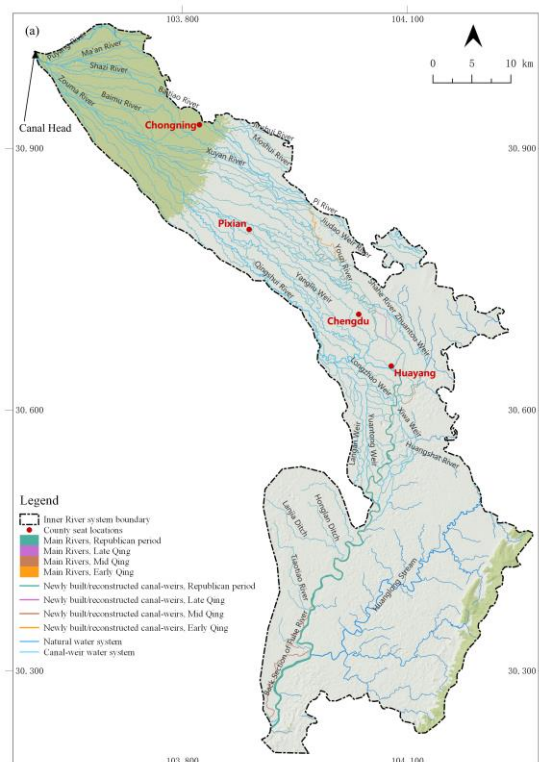


Figure 6. Reconstruction of the Lower Basin Network from the Qing to Republican period: (a) Early Qing; (b) Mid-Qing; (c) Late Qing; (d) Republican period.



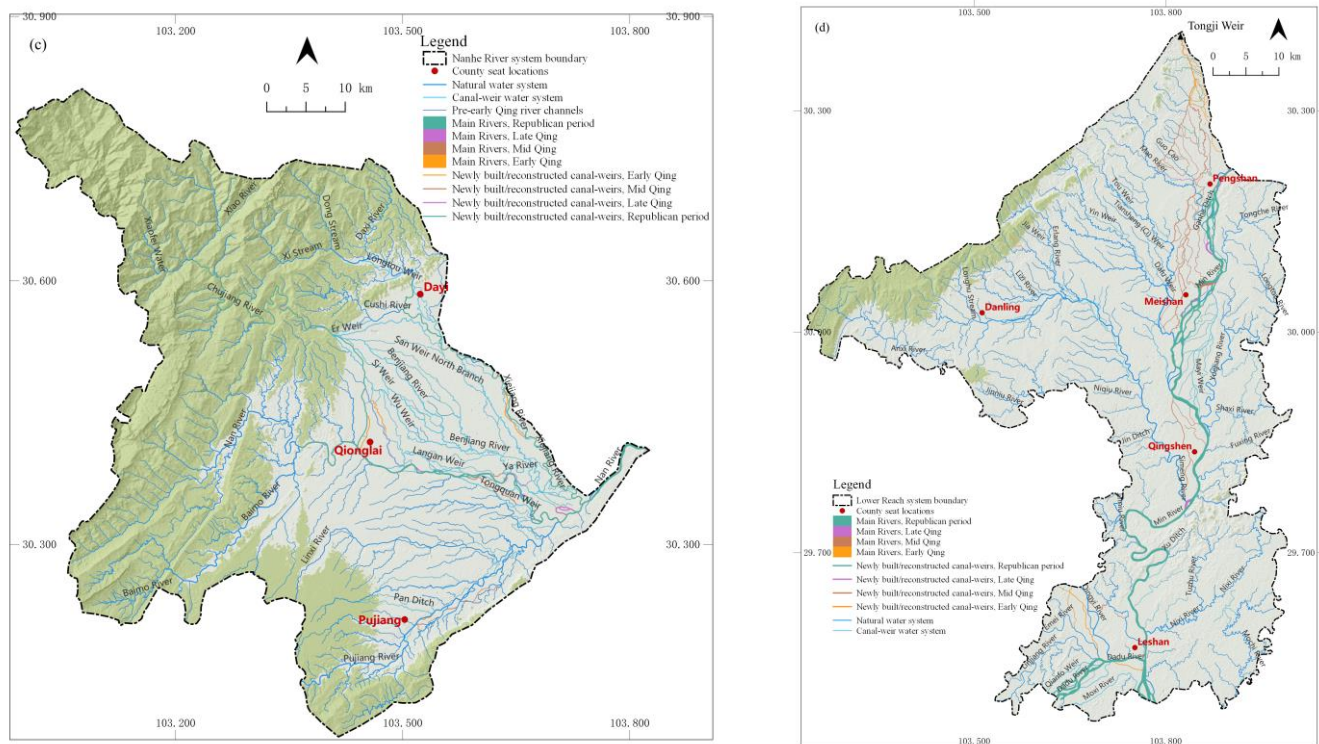


Figure 7. Summary of the Evolution of the River Network in the Middle Reaches of the Minjiang River from the Qing to Republican period: (a) Inner River; (b) Outer River; (c) Nanhe River; (d) Lower Basin.

- Inner River Subregion

From the Early to Mid-Qing period, major canal constructions such as Shidi Weir and Gufu Weir were completed [51], establishing the basic canal network pattern. During the Late Qing period, canal and weir changes were minimal and primarily related to maintenance activities. In the Republican period, records of weir damage and maintenance increased significantly, with systematic large-scale repairs carried out after multiple floods. River course changes were negligible, as the main rivers remained under continuous human regulation.

- Outer River Subregion

From the Early to Mid-Qing, major new constructions such as Dalang Weir, Changtong Weir, and the water diversion modifications of Tongji Weir were completed [52–54], establishing the canal network structure. In the Late Qing period, maintenance and damage events increased substantially, and during the Republican period, repairs and damage occurred frequently over a wide area. River course changes included bifurcation of the western section near Chongqing County during the Mid- to Late Qing period, with the western channel flowing into Baima River and becoming the main channel. Between the Late Qing and Republican periods, the main Minjiang channel shifted repeatedly between Jinma and Yangma rivers [36,52,53,55–56].

- Nanhe River Subregion

In the Early and Mid-Qing, new canals such as Xinkai Weir, Yongzeng Weir, Xugong Weir, Duangong Weir, and Zhanggong Weir were constructed [57,58], and 36 dikes and weirs were reconstructed [51]. During the Late Qing and Republican periods, only minor new constructions occurred. River course changes included a diversion of the Zhanjiang River in the Early Qing period, a diversion of the Xiejiang River during the Qianlong reign

(Mid-Qing), and channel straightening in the lower Nanhe River in 1914 (Republican period) [59].

- Lower Basin Subregion

From the Early to Mid-Qing, development focused on new construction and reconstruction, including large-scale projects such as Niute Weir, Botan Weir, Tongji Weir, Jianggong Weir, and Honghua Weir [51,60,61]. During the Late Qing period, new constructions were mostly small canals or weirs, accompanied by silting and abandonment processes; the main Minjiang channel began migrating westward, causing the diversion point of Mayi Weir to shift upstream in 1822 [37,62]. In the Republican period, the main channel continued its westward migration (1917), and the Mayi Weir diversion point shifted again [37,62]. Repairs and damage events were frequent during this period, primarily affecting Mayi Weir, and some weirs abandoned in the Late Qing were reconstructed [63].

4.2. Patterns of River–Canal Changes

4.2.1. Overall Change Patterns

Based on Table S2, river–canal change events were counted by period and subregion. The annual mean change intensities for anthropogenic construction and environmentally driven changes were calculated (Table 8), and the temporal variation of overall change intensity across the basin was illustrated in Figure 8.

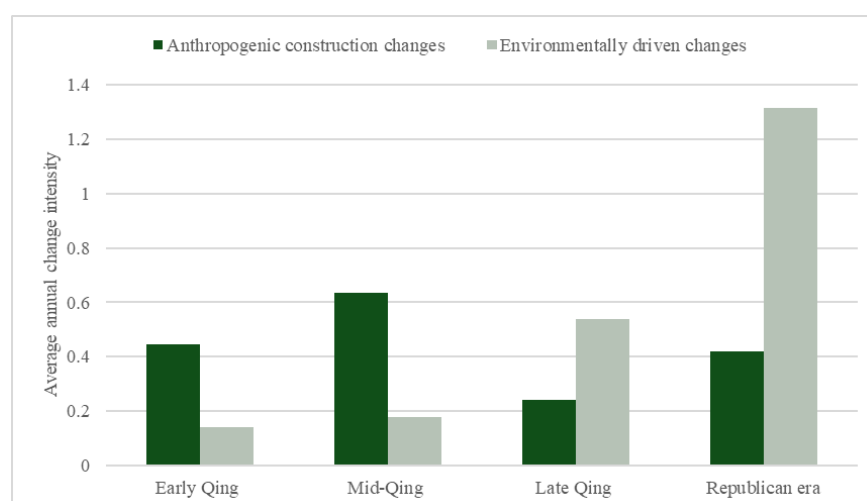


Figure 8. River–canal change intensity in the middle reaches of the Minjiang River (Qing–Republican Period).

Table 8. River–canal change intensity in the middle reaches of the Minjiang River (Qing–Republican Period).

Subregion	Anthropogenic Construction Change Intensity				Environmentally Driven Change Intensity			
	Early Qing	Mid-Qing	Late Qing	Republican	Early Qing	Mid-Qing	Late Qing	Republican
Canal Head	0.01	0	0	0.03	0.08	0.05	0.12	0.18
Inner River	0.04	0.06	0.02	0.05	0	0	0.02	0.32
Outer River	0.09	0.19	0.08	0.13	0.04	0.05	0.32	0.55
Nanhe River	0.07	0.13	0.01	0.03	0.01	0.01	0	0.03
Lower Basin	0.24	0.26	0.13	0.18	0.01	0.07	0.08	0.24
Total	0.45	0.64	0.24	0.42	0.14	0.18	0.54	1.32

Based on the above statistics and calculations, the temporal evolution of river–canal change intensity in the middle reaches of the Minjiang River can be summarized as

follows. Anthropogenic construction change intensity peaked during the Mid-Qing period (0.64), while environmentally driven change intensity reached its maximum in the Republican period (1.32). During the Early Qing period, changes were dominated by reconstruction activities, with relatively high anthropogenic intensity and the lowest environmentally driven intensity (0.14). In the Mid-Qing period, new construction activities reached their largest scale, driving anthropogenic intensity to its peak, while environmentally driven intensity remained low. In the Late Qing period, maintenance, damage, and rerouting events increased substantially, resulting in a marked increase in environmentally driven intensity, while anthropogenic intensity declined sharply. During the Republican period, the scale of maintenance and damage reached its maximum, leading to a surge in environmentally driven intensity, whereas anthropogenic intensity increased slightly. Overall, anthropogenic changes dominated the Early and Mid-Qing periods, while environmentally driven changes showed a continuous increase from the Late Qing period and reached a maximum in the Republican period.

4.2.2. Patterns by Subregion

Changes in river–canal intensity by subregion are shown in Figure 9.

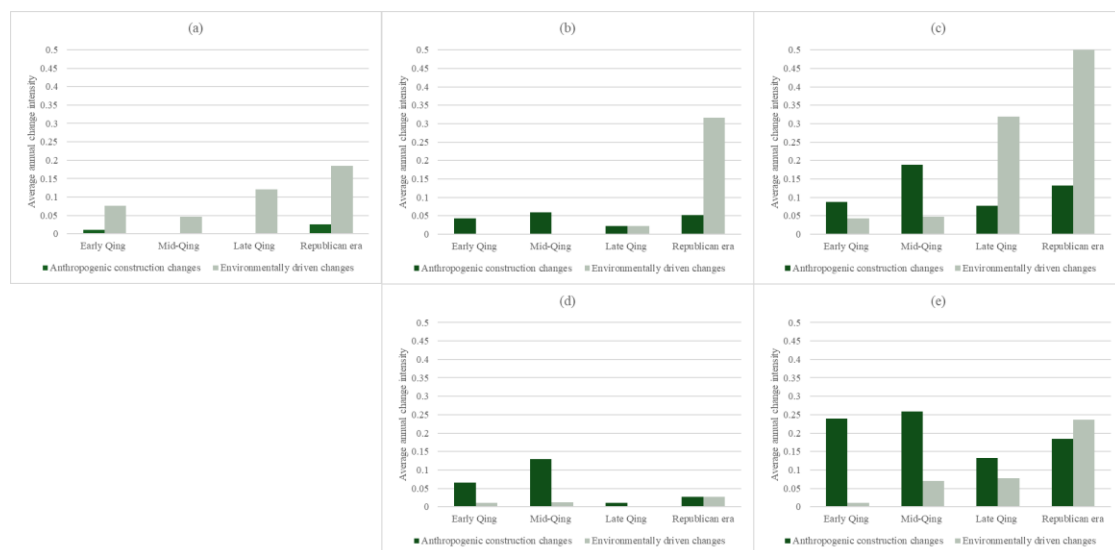


Figure 9. Temporal Variation in River–Canal Change Intensity at the Dujiangyan Canal Head and in Each Subregion from the Qing to Republican period: (a) Dujiangyan canal head; (b) Inner River; (c) Outer River; (d) Nanhe River; (e) Lower Basin.

- Dujiangyan Canal Head

Changes were primarily characterized by maintenance activities. The number of maintenance events was lowest in the Mid-Qing period (4 events) and increased steadily thereafter, reaching the highest level in the Republican period (7 major repairs over 38 years), with a change intensity of 0.18.

- Inner River Subregion

River–canal change intensity remained generally low during the Qing period. In the Late Qing period, environmentally driven intensity was 0.02, lower than that of the Outer River subregion (0.32). By the Republican period, six large-scale damage and repair events were recorded, and environmentally driven intensity increased to 0.32.

- Outer River Subregion

The Outer River exhibited the highest overall change intensity in the basin (1.44). Anthropogenic construction intensity peaked in the Mid-Qing period (0.19).

Environmentally driven intensity was low during the Early and Mid-Qing periods, increased to 0.32 in the Late Qing period (accounting for over 80% of total changes during this period), and further rose to 0.55 in the Republican period.

- Nanhe River Subregion

This subregion showed the lowest river–canal change intensity among the four subregions (0.28). Except for the Mid-Qing period, no major anthropogenic or environmentally driven changes were recorded, and intensity remained relatively stable across periods.

- Lower Basin Subregion

The Lower Basin recorded the highest number of change events (76). During the Early Qing, 10 new constructions and 9 reconstructions were recorded. In the Mid-Qing period, anthropogenic intensity reached 0.26, accompanied by a slight increase in environmentally driven intensity. During the Late Qing period, anthropogenic intensity declined by about 50% relative to the Mid-Qing. In the Republican period, environmentally driven intensity peaked at 0.24, the highest level among all periods for this subregion.

4.3. Results of Driving Mechanisms

4.3.1. Temporal Characteristics of Driver Variables

Detailed values of the seven driver variables (X1–X7) for the four study periods and subregions are provided in Table A2.

The drought factor (X1) remained generally low. In the Inner River, Outer River, and Nanhe River subregions, values were small and showed a decreasing trend. In the Lower Basin, X1 surged to 0.069 during the Late Qing period, the highest in the basin, and decreased to 0.020 in the Republican period, although still higher than in other subregions.

The flood factor (X2) exhibited an overall upward trend. In the Inner River, X2 was low during the Qing period (0.006–0.031) but increased sharply to 0.113 in the Republican period. In the Outer River, X2 rose steadily from 0.003 in the Early Qing period to 0.156 in the Republican period. The Nanhe River consistently showed the lowest values across all periods. In the Lower Basin, X2 increased to 0.091 in the Mid-Qing period and remained high thereafter.

The wet–dry factor (X3) was lowest in the Mid-Qing period (0.062), indicating the relatively stable climate, whereas the Early Qing (0.282) and Republican period (0.221) showed large wet–dry fluctuations, suggesting higher probabilities of extreme droughts and floods.

The temperature factor (X4; Table A3) was derived from temperature fluctuation grading (Table 5) combined with historical climate studies in Southwest China [6,64–68]. Values were lowest in the Mid-Qing period (0.3) and highest in the Republican period (0.8), indicating relatively weak temperature fluctuations in the Mid-Qing and stronger variability in the Republican period. The high value (0.8) in the Republican period reflects the pronounced cold–warm alternation. Tree-ring evidence from western Sichuan shows that 1941–1960 was a relatively warm period, while 1831–1940 was a persistent cold period, suggesting that the 19th–20th centuries experienced pronounced climatic variability [6]. This pattern is broadly consistent with the winter temperature reconstruction for eastern China, which identifies the 1920s–1940s as a relatively warm period following a prolonged cold phase (1830–1889) [67]. The rapid transition from prolonged cold to warmer conditions within a few decades indicates strong temperature variability during the study period.

The population factor (X5) was generally higher in the Early and Mid-Qing periods, peaking at 2.09–2.86% in the Mid-Qing period. It declined sharply in the Late Qing period (0.02–0.18%). In the Republican period, population growth rebounded markedly in the

Nanhe River (2.27%) and Lower Basin (1.57%), while remaining low in the Inner River (0.20%) and Outer River (0.10%) (Table A4).

The canal head control factor (X6) reached its lowest value (0.047) in the Mid-Qing period, increased during the Late Qing period, and peaked in the Republican period (0.211). This indicates that the canal head condition and hydraulic regulation were relatively favorable in the Mid-Qing period and comparatively weaker during the Republican period.

The river network structure factor (X7) was fixed for each subregion. The Nanhe River had the highest value (151.61), followed by the Inner River (105.23), Outer River (86.22), and Lower Basin (46.33). Higher X7 values in the Nanhe and Inner River subregions indicate a more complete river order structure and relatively more balanced channel length distribution, reflecting higher network complexity. Conversely, the Outer River and Lower Basin had lower network complexity, suggesting less optimal ratios between total river length and the highest-order river lengths.

4.3.2. Overall Correlation Characteristics

Pearson correlation analysis for the full sample (Table 9) was conducted to examine the contributions of each driver variable to the two types of water environment changes. The relative contributions of the drivers are illustrated in Figure 10.

Table 9. Pearson correlation analysis between water environment changes and driver variables.

Driver Variable	Y1 (r)	Y1 (p)	Y2 (r)	Y2 (p)
X1 (Drought)	0.190	0.481	−0.078	0.773
X2 (Flood)	0.264	0.322	0.803	0.0002 ***
X3 (Wet–Dry)	−0.157	0.562	0.132	0.625
X4 (Temperature)	−0.303	0.253	0.416	0.109
X5 (Population)	0.397	0.128	−0.539	0.031 *
X6 (Canal Head Control)	−0.256	0.339	0.648	0.007 **
X7 (River Network Structure) †	−0.724	0.001	−0.27	0.311

Notes: * $p < 0.05$ (significant), ** $p < 0.01$ (highly significant), *** $p < 0.001$ (extremely significant). † X7 is a time-invariant structural property of each subregion; its correlation reflects cross-subregional structural differences rather than temporal dynamics.

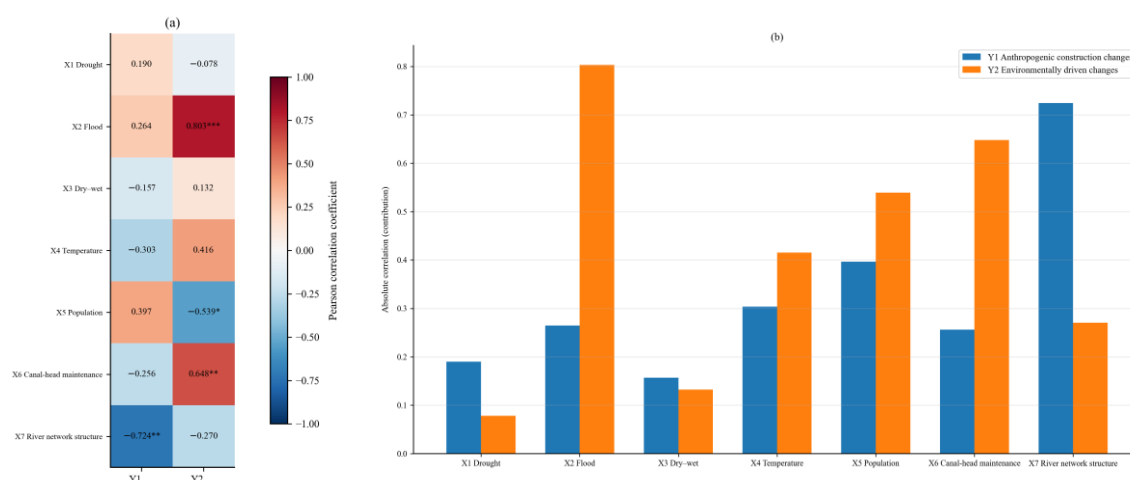


Figure 10. Analysis of Driving Factors for River–Canal Changes: (a) Correlation heatmap for the full sample; (b) Contribution of driving factors. * $p < 0.05$ (significant), ** $p < 0.01$ (highly significant), *** $p < 0.001$ (extremely significant).

Among the driver variables, river network structure (X7) showed the strongest association with Y1 ($r = -0.724$), indicating that subregions with more complex and well-developed river networks tend to have lower anthropogenic construction intensity. This association reflects cross-subregional structural differences rather than temporal variation. Population (X5) acts as a positive driver ($r = 0.397$), whereas temperature (X4) exerts a slight inhibitory effect ($r = -0.303$).

For environmentally driven changes (Y2), the main driver is the flood factor (X2, $r = 0.803$, $p < 0.001$), followed by canal head control (X6, $r = 0.648$, $p < 0.01$). In addition, Y2 is negatively correlated with population (X5, $r = -0.539$, $p < 0.05$) and positively correlated with temperature (X4, $r = 0.416$, not significant).

4.3.3. Regional Differences in Correlations

Subregional analyses (Table 10, Figures 11 and 12) reveal spatial heterogeneity in driving mechanisms.

Table 10. Subregional Correlations between Two Types of Water Environment Changes and Driver Variables.

Dependent Variable	Subregion	X1 (Drought)	X2 (Flood)	X3 (Wet–Dry)	X4 (Temperature)	X5 (Population)	X6 (Canal Head Control)
Y1 (Anthropogenic Construction)	Inner River	0.483	0.476	−0.073	−0.265	0.605	−0.089
	Outer River	0.283	0.103	−0.592	−0.652	0.527	−0.270
	Nanhe River	−0.593	0.118	−0.431	−0.790	0.629	−0.757
	Lower Basin	−0.942	−0.477	−0.006	−0.455	0.980	−0.587
Y2 (Environmentally Driven)	Inner River	−0.630	0.970	0.310	0.630	−0.574	0.924
	Outer River	−0.973	0.955	0.163	0.635	−0.895	0.957
	Nanhe River	−0.755	0.708	0.351	0.403	0.789	0.595
	Lower Basin	0.043	0.612	0.039	0.435	−0.160	0.863

Notes: Correlations are based on $n = 4$ per subregion; results should be interpreted with caution.

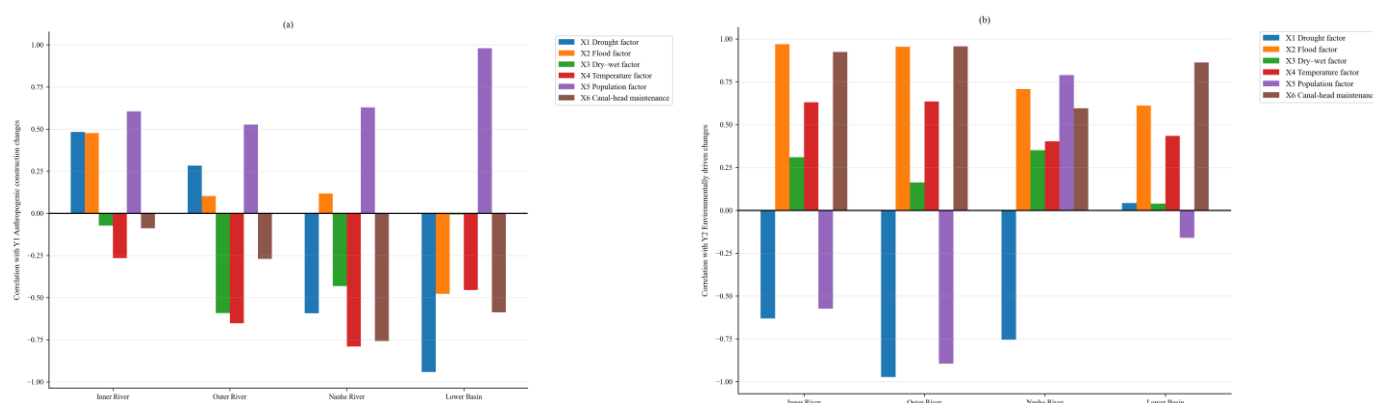


Figure 11. Correlations between Driver Variables and River–Canal Changes: (a) Anthropogenic Construction Changes; (b) Environmentally Driven Changes.

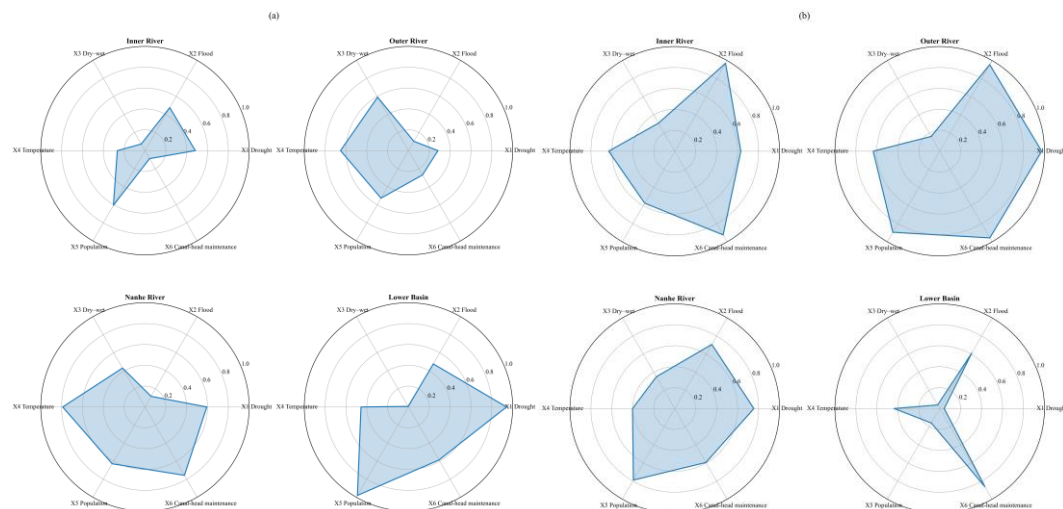


Figure 12. Radar Plots Comparing the Contributions of Driver Variables to River–Canal Changes by Subregion: (a) Anthropogenic Construction Changes; (b) Environmentally Driven Changes. The values along the radial axis represent Pearson correlation coefficients.

In the Inner River, anthropogenic construction changes (Y1) were primarily driven by population (X5, $r = 0.605$). Environmentally driven changes (Y2) showed a strong directional association with flood factor (X2, $r = 0.970$) and canal head control (X6, $r = 0.924$).

In the Outer River, Y1 showed a negative association with temperature fluctuations (X4, $r = -0.652$) and wet–dry variability (X3, $r = -0.592$), and a positive association with population growth (X5, $r = 0.527$). Y2 showed a strong directional association with drought (X1, $r = -0.973$), flood (X2, $r = 0.955$), and canal head control (X6, $r = 0.957$). The association between X1 and Y2 is likely spurious due to extremely low drought indices in this subregion. Y2 also showed a strong negative directional association with population (X5, $r = -0.895$).

In the Nanhe River, Y1 showed a positive association with population (X5, $r = 0.629$) and negative associations with drought (X1, $r = -0.593$), temperature fluctuations (X4, $r = -0.790$), and canal head control (X6, $r = -0.797$). The X1–Y1 associations are likely spurious due to near-zero drought index values in this subregion; therefore, Y2 values were extremely low (≤ 0.03), and these correlation results have limited practical significance.

In the Lower Basin, Y1 showed a strong positive association with population growth (X5, $r = 0.980$) and a strong negative directional association with drought (X1, $r = -0.942$). Y2 showed positive associations with canal head control (X6, $r = 0.863$) and flood (X2, $r = 0.612$).

5. Discussion

5.1. Overall Characteristics of River–Canal Change Drivers

Based on the correlation analysis, the overall drivers of river–canal changes in the middle reaches of the Minjiang River from 1644 to 1949 can be summarized as follows. Anthropogenic construction changes (Y1) are primarily constrained by river network complexity, promoted by population growth, and slightly inhibited by temperature fluctuations. Environmentally driven changes (Y2) are mainly driven by floods, intensified when canal head regulation failed, with temperature fluctuations exerting indirect effects.

The flood factor (X2) is highly positively correlated with Y2 but weakly and non-significantly correlated with Y1. Flooding drives environmentally induced changes, directly causing channel rerouting and weir damage, but it rarely affects new construction or reconstruction. Concentrated precipitation and abundant upstream inflow in the

middle Minjiang make flooding the primary stressor for water environment instability. Frequent floods from the Late Qing to Republican periods, together with sustained increases in Y2 intensity, further support this causal relationship.

The canal head control factor (X6) is strongly positively correlated with Y2 but not significantly correlated with Y1, indicating that canal head regulation is critical for water environment stability but unrelated to the execution of water engineering. Higher X6 values indicate greater maintenance requirements and thus reduced regulation performance. When maintenance requirements were low in the Early–Mid Qing period, overall water environment stability was high. From the Late Qing period, Y2 increased in tandem with X6, and by the Republican period, canal head disorder led to a surge in Y2. This temporal coupling demonstrates that effective operation of Dujiangyan can substantially mitigate flood impacts, while regulation failure exacerbates environmental instability.

The river network structure factor (X7) shows a strong negative association with Y1 and a weak association with Y2. Subregions with more developed natural channels and canal systems (e.g., Nanhe and Inner River subregions) are associated with lower anthropogenic construction intensity, whereas subregions with simpler network structures and weaker regulation capacity (e.g., Lower Basin) are associated with higher levels of anthropogenic interventions. This highlights the fundamental constraint imposed by natural conditions: a well-structured river network inherently provides hydrological regulation, reducing the need for additional engineering interventions.

The population factor (X5) shows opposite correlations with the two types of changes. X5 is positively correlated with Y1, indicating that population growth drives water engineering activities. During the Mid-Qing period, when population growth peaked, Y1 reached its highest value, confirming this relationship. X5 is negatively correlated with Y2, but this does not imply a causal effect. The negative correlation reflects temporal coincidence: warfare at the end of the Ming and early Qing periods reduced Sichuan's population to roughly 10% of mid-Ming levels; in the Early–Mid Qing period, population rapidly increased due to state migration policies [69], while flooding was infrequent and Y2 remained low. In the Late Qing period, population growth slowed, flooding intensified, and Y2 increased. Thus, the negative correlation should not be interpreted as population suppressing Y2. Instead, long-term population growth and the associated pressures on land use and water resources likely contributed to declining water environment stability from the Late Qing to Republican periods.

Temperature fluctuations (X4) have relatively weak effects on both types of changes. X4 is negatively correlated with Y1, indicating that greater climatic instability (frequent extreme cold or heat events) reduces the capacity or willingness for large-scale engineering. X4 is positively correlated with Y2, suggesting that temperature variability indirectly affects water environment stability by intensifying wet–dry alternation and extreme hydrological events, though its influence is masked by more direct drivers such as floods and canal head regulation.

The drought factor (X1) and wet–dry factor (X3) show no significant correlations with Y1 or Y2 at the basin-wide scale, indicating that they are not primary drivers of overall river–canal changes, although their effects may be more pronounced in specific subregions.

5.2. Regional Differentiation and Patterns of Driving Mechanisms

Subregional correlation analyses reveal clear differences in the driving mechanisms across the four river systems, leading to the identification of four distinct driver patterns (Figure 13). This spatial heterogeneity is primarily associated with the interplay of natural environment, regional position, and hydraulic regulation effectiveness (Table 11).

Table 11. Driving Mechanism Patterns of River–Canal Changes and Their Causes.

Subregion	Driver Pattern	Description	Feature	Key Factors
Inner River	Human-Dominated Intervention	Population growth drives water engineering; water environment stability highly dependent on effective canal head regulation	Human-dominated	Favorable natural conditions; core area of the protected irrigation system; strong hydraulic regulation
Outer River	Flood Stress	Water engineering driven by population but constrained by climate; floods induce water environment instability	Nature-dominated	Weak network retention capacity; flood conveyance area; high natural flood frequency; weak regulation
Nanhe River	Low-Disturbance Stability	Water engineering driven by population growth, but overall change intensity remains low and environmentally stable	Low-disturbance	Geographically isolated; well-structured network; auxiliary location; low-energy environment
Lower Basin	Natural–Human Composite	Population growth strongly drives construction; water environment stability controlled by upstream hydrology (canal head regulation, floods)	Natural–human composite	Poor natural conditions; downstream location; upstream hydrological control; irrigation expansion area

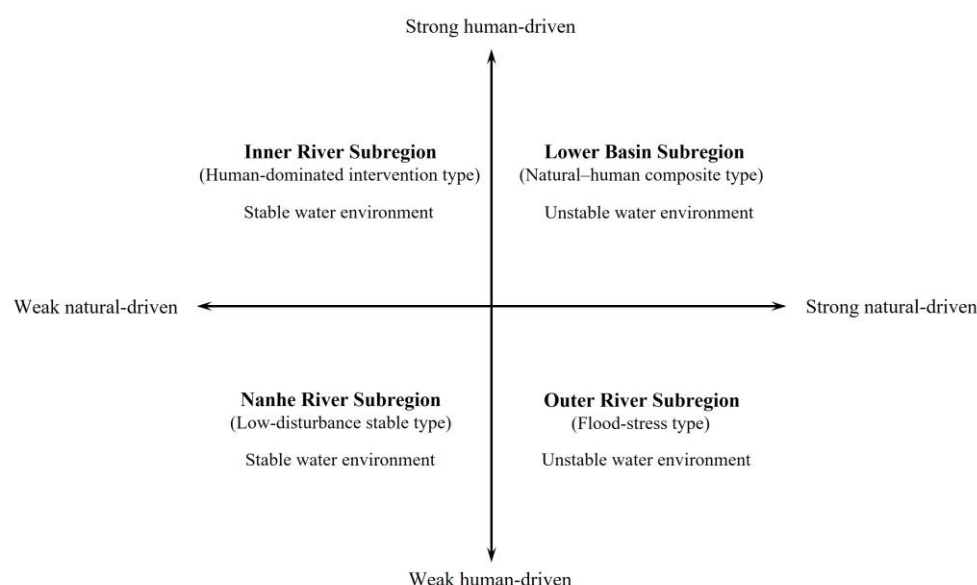


Figure 13. Four-quadrant representation of the patterns of driving mechanisms. Subregions are placed based on the absolute Pearson correlation coefficients from Table 10: human-driven if $|r|$ for any human-related driver (X_5, X_6) > 0.6 ; natural-driven if $|r|$ for any natural driver (X_1, X_2, X_3, X_4) > 0.6 ; composite if both conditions are met; weak if all $|r| < 0.4$.

- **Inner River: Human-Dominated Intervention**

In the Inner River, Y1 shows a strong association with population growth, while Y2 shows close associations with floods and canal head regulation. The subregion benefits from favorable natural conditions: located on the plain with a dense and complex river network ($R_c = 105.23$) and substantial storage capacity. As part of the core irrigation area of Dujiangyan, it has long maintained relatively stable operation under the “4:6 water diversion” mechanism and Qing-period official maintenance practices [4]. Consequently, water environment stability was highest during the Qing period (Y2 near zero). However, once hydraulic regulation failed in the Republican period, excessive floodwater combined with meandering channels that hindered rapid drainage caused Y2 to surge to 0.32. This

demonstrates that water environment stability in the Inner River is highly dependent on human interventions, characteristic of a human-dominated intervention pattern.

- **Outer River: Flood-Stress Pattern**

In the Outer River, Y1 is positively driven by population growth but constrained by temperature and wet–dry fluctuations, while Y2 is closely linked to floods and canal head control. The subregion lies on a plain with straight, dense channels capable of rapid flood conveyance, consistent with its role as a flood corridor. However, its river network is simple ($R_c = 86.22$) and lacks storage areas, limiting regulation during extreme, prolonged floods. Historically, Dujiangyan allocated 60% of floodwater to the Outer River during the flood season, making it naturally more flood-prone than the Inner River. In addition, limited official maintenance during the Qing period [4] further reduced hydraulic regulation effectiveness. Thus, flooding is the primary stressor for Y2, and the high correlation with X6 reflects covariance rather than direct causation. Overall, the Outer River exhibits a nature-dominated flood-stress driver pattern.

- **Nanhe River: Low-Disturbance Stability**

In the Nanhe River, Y1 is positively correlated with population growth and negatively with canal head control, while Y2 remains near zero with no effective drivers. Located in the transitional zone between mountains and plains, the subregion has a well-developed river network ($R_c = 151.61$), which contributes to natural flood attenuation. Being distant from the Dujiangyan canal head and not situated on major flood conveyance channels, X6's negative correlation with Y1 is incidental. The subregion is geographically isolated with low irrigation demand, resulting in minimal human intervention. The combination of limited anthropogenic pressure, favorable network structure, and geographic isolation corresponds to a low-disturbance, stable pattern.

- **Lower Basin: Natural–Human Composite**

In the Lower Basin, Y1 is primarily driven by population growth and strongly negatively correlated with drought. This pattern reflects the delayed response of water engineering activity to drought: during severe droughts, social resources focused on relief, whereas drought-induced soil degradation and repeated canal silting impeded construction; recovery projects were concentrated post-disaster. Severe Late Qing droughts led to silted or abandoned weirs, reducing Y1, while reconstruction activities in the Republican period increased Y1. Y2 is driven by canal head regulation and flooding, indicating that water environment stability is closely linked to upstream hydrological conditions.

The subregion has poor natural conditions: located in basin hills, with a simple, heavily channelized network ($R_c = 46.33$), single drainage pathways, and higher drought–flood risk. Water conditions in this downstream area are strongly influenced by upstream inflow, increasing flood risk. As an irrigation expansion area, population growth strongly promotes water engineering activities, primarily for agricultural development, but overall hydraulic regulation remains limited. These factors collectively result in frequent droughts and floods and an unstable water environment. River–canal changes in this subregion are driven by population and canal head regulation (human factors) as well as drought and flood events (natural factors), exhibiting a natural–human composite pattern.

5.3. The “Double-Edged Sword” Effect of Dujiangyan Canal Head Regulation

From the Mid-Qing to the Republican period, the wet–dry factor (X3) in the basin increased steadily, reflecting higher interannual precipitation variability and an increased likelihood of extreme floods. However, the Inner and Outer River subregions respond differently under this climatic background, highlighting the critical role of canal head regulation in maintaining water environment stability.

In the Late Qing period, X3 rose from 0.06 to 0.13. In the Outer River, the flood index increased from 0.050 to 0.089, and environmentally driven change intensity (Y2) surged accordingly. By contrast, in the Inner River, canal head regulation remained relatively effective, keeping the flood index at a low level (0.011) and Y2 also remaining low. This contrast demonstrates the proper functioning of the Dujiangyan diversion mechanism: most floodwater was directed to the Outer River, protecting the core irrigation area of the Inner River. By the Republican period, X3 further increased to 0.221, with extreme hydrological events becoming more frequent. Simultaneously, X6 rose sharply and regulation efficiency declined, reflecting the combined influence of increased hydrological stress and institutional disruption under social instability. Previously intercepted floodwater breached the canal head, inundating the Inner River, raising its flood index to 0.113 and triggering a surge in Y2. Flood index (0.156) and Y2 (0.55) in the Outer River also increased. Consequently, both subregions entered a highly vulnerable state.

This comparison reveals a “double-edged sword” effect: in heavily engineered river systems, effective maintenance can minimize the impact of droughts and floods, stabilizing the water environment, whereas inadequate maintenance can release previously controlled hazards, subjecting protected areas to more severe environmental stress. This underscores the critical importance of hydraulic maintenance and management.

5.4. Comparison with Previous Studies and Research Prospects

This study confirms that floods are the primary natural driver of environmentally driven changes (Y2), consistent with the frequent precipitation fluctuations and enhanced hydrological variability in Southwest China since the Little Ice Age [70,71]. The increasing variability of the wet–dry factor (X3) from the Mid-Qing to Republican period also supports this trend. Regionally, the cold-wet characteristics of the western Sichuan Basin during the Little Ice Age [72] and six episodes of increased precipitation in the mid- to late Qing period [7] correspond with periods of elevated flood index (X2) in this study. Multi-scale climatic evidence validates the conclusion that floods are the main driver of Y2.

Canal head regulation is identified as a key human driver of Y2. Previous research indicates that water engineering can both stabilize and disrupt the water environment [73–76], particularly when maintenance is insufficient, leading to soil erosion and environmental degradation [76]. The Dujiangyan system, which integrates water control and utilization, exemplifies the ancient principle of “following natural trends and adapting to local conditions.” Its sustainability depends on the combined support of technology, institutions, and society [5]. The strong correlation between X6 and Y2 observed here quantitatively demonstrates the pivotal role of maintenance in water environment stability, providing empirical insight into the “maintenance–efficiency–environment feedback” mechanism of large hydraulic projects.

Additionally, this study reveals pronounced spatial heterogeneity in river–canal changes within the middle Minjiang River, with the four subregions exhibiting distinct driving patterns. This indicates that variations in natural geography, regional functional positioning, and water management intensity can produce fundamentally different water environment trajectories within the same basin. The subregional driver pattern framework offers a methodological reference to avoid treating complex basins as homogeneous systems, facilitating comparative studies on basin governance.

The study has several limitations: historical sources exhibit spatiotemporal resolution gaps; some human factors are difficult to quantify fully; and the characterization of driving mechanisms relies primarily on correlation analysis, limiting the exploration of complex nonlinear feedbacks. Additionally, a potential circularity may exist between the canal head control factor (X6) and environmentally driven changes (Y2), as major floods can simultaneously elevate both. Future research could integrate multidisciplinary

approaches, such as ground-penetrating radar or environmental DNA, to construct higher-resolution water environment evolution sequences, expand temporal and spatial coverage, and quantify the influence of water rights systems, social institutions, and cultural factors.

6. Conclusions

This study reconstructs the spatiotemporal evolution of river–canal changes in the middle reaches of the Minjiang River from 1644 to 1949 using historical documents, historical maps, remote sensing imagery, and field surveys. It quantifies the intensity of anthropogenic construction and environmentally driven changes and identifies the multiple natural and human factors. The main conclusions are as follows:

- River–canal changes exhibit pronounced spatial heterogeneity. In the Inner River, canal head regulation during the Qing maintained low change intensity, whereas the collapse of hydraulic structures in the Republican period triggered a surge in environmentally driven changes. The Outer River experiences the highest overall change intensity, dominated by anthropogenic construction in the Early–Mid Qing, with environmentally driven changes increasing sharply after the Late Qing period due to floods. The Nanhe River shows the lowest and most stable change intensity over time. The Lower Basin is the most active, undergoing a complete trajectory from hydraulic expansion to maintenance-focused interventions.
- At the basin scale, anthropogenic construction changes are primarily constrained by natural conditions and promoted by population growth. Environmentally driven changes are mainly triggered by floods and intensified when hydraulic regulation fails.
- The four subregions exhibit distinct driving mechanism patterns: (1) Inner River—human-dominated intervention, where population growth is strongly associated with water engineering activity and stability is closely linked to canal head regulation; (2) Outer River—flood-stress pattern, where water engineering activity is associated with population but constrained by climate, while environmental changes are strongly associated with flood variability; (3) Nanhe River—low-disturbance stable pattern, characterized by a long-term stable water environment; (4) Lower Basin—natural–human composite pattern, where engineering activity is associated with population growth and environmental variability is mainly linked to upstream hydrological conditions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/w18131575/s1>: Table S1: Compilation of Historical Documents and Records; Table S2: Statistical Data on River and Canal Changes.

Author Contributions: Conceptualization, Y.Y.; methodology, Y.Y.; software, Y.Y. and T.H.; validation, Y.Y., T.H. and Q.D.; formal analysis, Y.Y.; investigation, Y.Y. and T.H.; resources, Y.Y. and Q.D.; data curation, Y.Y.; writing—original draft preparation, Y.Y.; writing—review and editing, Y.Y.; visualization, Y.Y. and T.H.; supervision, Y.Y.; project administration, Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The Kangxi “Imperial Map by Province and Prefecture” is from the China Historical GIS platform, Fudan University (<http://timespace-china.fudan.edu.cn/>) (accessed on 25 December 2022). Republican-era 1:50,000 and 1:100,000 maps are from the Academia Sinica Center for Digital Humanities “Integrated Map Digital Archive” (<https://gis.ascc.net/mapdb/>) (accessed on 21 September 2022). Sentinel-2 imagery was obtained from the ESA Copernicus Open

Access Hub (<https://scihub.copernicus.eu>) (accessed on 24 February 2024). Qing and Republican local gazetteers are mainly from Collection of Sichuan Historical Local Gazetteers (National Library Press, 2017 facsimile), with some accessed via Sichuan Provincial Library. Official histories and hydrology/geography monographs were accessed through the National Digital Library of China (<http://www.nlc.cn>) (accessed on 20 March 2026). The four hydraulic thematic maps (Table 1) are sourced from publicly available water conservancy gazetteers, county records, and archives (see references [26,54]). Base geographic data (administrative boundaries, ASTER GDEM V3, etc.) are from the Geospatial Data Cloud (<http://www.gscloud.cn>) (accessed on 17 May 2022). Detailed lists of water cultural heritage sites, including coordinates, types, and dating, are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to express their sincere gratitude to Zhao Bing, Qi Shihua, Peng Jing, Gu Yansheng, Chen Kunlun, Li Jiangfeng and Wang Qi for their valuable help and support. We also thank the staff of the Sichuan Provincial Library and the National Digital Library of China for providing access to historical documents and old maps, as well as the Center for Historical Geographical Studies, Fudan University, and the Academia Sinica for providing digital map resources. Finally, we extend our thanks to the local villagers for sharing their oral histories and local knowledge during the field investigations.

Conflicts of Interest: Author Tianhua Han was employed by the company China Wuhuan Engineering Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Appendix A

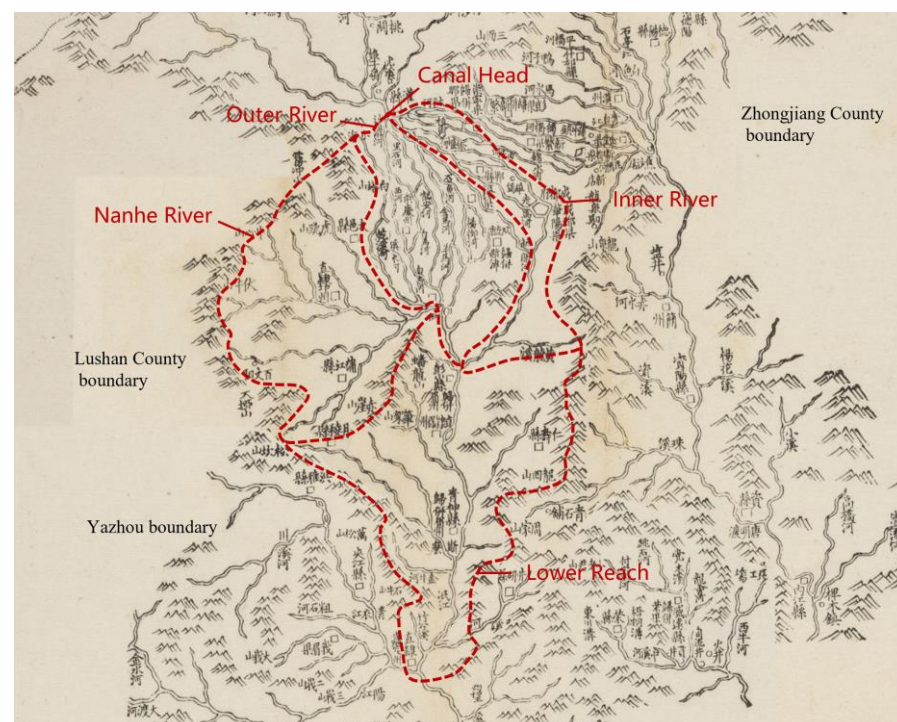


Figure A1. Partial map of Sichuan Province from the Kangxi “Imperial Map by Province and Prefecture.”

Table A1. Classification criteria for drought and flood events in the middle Reaches of the Minjiang River.

Type	Value	Criteria	Example
Flood	1	Heavy and long-lasting precipitation, extensive flooding, or extreme storms causing severe damage	“June flood, water in Baijiang River rose several feet and lasted over ten days”; “Severe flood destroyed numerous fields, houses, and bridges”; “On the night of June 20, flood surged at Xuan Kou Chang Mountain, sweeping away dozens of houses and killing over 300 people”
Moderate Flood	2	Seasonal moderate precipitation, localized flooding, or less severe heavy rain events	“Water rise,” “Flood,” “Heavy rain,” “Autumn flood,” “July flood,” “River overflow damaged crops,” “Summer flood causing crop loss,” “Water breached embankments”
Normal	3	Abundant harvests or no recorded drought/flood events	“Bumper harvest,” “Good year,” “Autumn yield was abundant,” “Crops showed signs of dual growth”
Moderate Drought	4	Seasonal or monthly minor drought, localized	“Spring drought,” “Drought,” “Severe drought,” “Severe drought, rain began in June”
Severe Drought	5	Prolonged drought over several months or across seasons, widespread or severely damaging	“No rain from March to July,” “Summer drought, rivers dried up,” “Widespread crop failure and famine,” “Severe drought, 30 <i>dou</i> of rice sold for gold, people unable to farm, resorted to cannibalism”

Table A2. Raw data for driver variables and dependent variables in the middle Minjiang River (Qing to Republican period).

Period	Subregion	Y1	Y2	X1	X2	X3	X4	X5	X6	X7
Early Qing	Inner River	0.04	0.00	0.006	0.006	0.28	0.7	2.00	0.09	105.23
Early Qing	Outer River	0.09	0.04	0.009	0.003	0.28	0.7	1.64	0.09	86.22
Early Qing	Nanhe River	0.07	0.01	0.000	0.004	0.28	0.7	1.92	0.09	151.61
Early Qing	Lower Basin	0.24	0.01	0.009	0.016	0.28	0.7	2.16	0.09	46.33
Mid Qing	Inner River	0.06	0.00	0.006	0.031	0.06	0.3	2.62	0.05	105.23
Mid Qing	Outer River	0.19	0.05	0.011	0.050	0.06	0.3	2.09	0.05	86.22
Mid Qing	Nanhe River	0.13	0.01	0.000	0.063	0.06	0.3	2.35	0.05	151.61
Mid Qing	Lower Basin	0.26	0.07	0.002	0.091	0.06	0.3	2.86	0.05	46.33
Late Qing	Inner River	0.02	0.02	0.000	0.011	0.13	0.6	0.02	0.12	105.23
Late Qing	Outer River	0.08	0.32	0.006	0.089	0.13	0.6	0.03	0.12	86.22
Late Qing	Nanhe River	0.01	0.00	0.011	0.026	0.13	0.6	0.18	0.12	151.61
Late Qing	Lower Basin	0.13	0.08	0.069	0.098	0.13	0.6	0.06	0.12	46.33
Republican	Inner River	0.05	0.32	0.000	0.113	0.22	0.8	0.20	0.21	105.23
Republican	Outer River	0.13	0.55	0.000	0.156	0.22	0.8	0.10	0.21	86.22
Republican	Nanhe River	0.03	0.03	0.000	0.083	0.22	0.8	2.27	0.21	151.61
Republican	Lower Basin	0.18	0.24	0.020	0.095	0.22	0.8	1.57	0.21	46.33

Table A3. Temperature fluctuation assignments for the middle Minjiang River (Qing to Republican period).

Period	Fluctuation Value	Reconstructed Temperature Anomaly Reference	Climate Characteristic
Early Qing	0.7	~1.0–2.0 °C below the 1951–1980 mean	Peak of the Little Ice Age, frequent extreme cold events
Mid Qing	0.3	~0.3–0.4 °C below the 1951–1980 mean	Relatively stable climate with mild fluctuations
Late Qing	0.6	1830–1889 cold period, coldest 1840–1869 (~1.5 °C below 1951–1980 mean)	Reduced climate stability, increased alternation of cold and warm periods

Period	Fluctuation Value	Reconstructed Temperature Anomaly Reference	Climate Characteristic
Republican	0.8	1920s–1940s: ~0.3–0.4 °C above the 1951–1980 mean	Most pronounced cold–warm alternation; rapid transition from cold to warm extremes

Table A4. Population data for four subregions (Qing to Republican period).

Subregion	1685 (Est.)	1812	1910 (Corrected)	1925 (Corrected)
Inner River	49,243	1,053,859	1,070,000	1,103,000
Outer River	80,883	874,941	900,000	913,500
Nanhe River	30,494	469,836	560,000	783,865
Lower Basin	29,788	798,918	850,000	1,068,393

References

- Xu, R. Climate Change in Mainland China during the Ming and Qing Dynasties. *J. Cap. Norm. Univ.* **2009**, *30*, 67–70. <https://doi.org/10.19789/j.1004-9398.2009.06.016>.
- Xu, J.H. *Climate Creates History*; SDX Joint Publishing Company: Beijing, China, 2006.
- Zhao, B. Revere Rivers: Living in the Embrace of Watersheds. *Huazhong Archit.* **2016**, *34*, 3–6. <https://doi.org/10.13942/j.cnki.hzjz.2016.09.002>.
- Tan, X.M. *History of Dujiangyan*; China Water & Power Press: Beijing, China, 2009.
- Hu, X. A Preliminary Study on the Uniqueness of Weir Canal System in Western Sichuan Plain. *Sichuan Archit.* **2014**, *34*, 13–15.
- Qin, N.S.; Shi, X.H.; Shao, X.M.; Wang, Q.C. Maximum Mean Air Temperature Indicated by Tree Rings in the Western Sichuan Plateau. *Plateau Mt. Meteorol. Res.* **2008**, *28*, 18–24.
- Hou, Y.L.; Zhao, J.B.; Hu, Y. Flood Disasters and Climatic Characteristics in Dujiangyan Area during the Qing Dynasty. *J. Mt. Sci.* **2017**, *35*, 865–873.
- Wang, S.; Hui, F.P. A Textual Study on the Evolution of the Fish Mouth Water Dividing Project of the Inner and Outer Rivers of Dujiangyan. *Anc. Mod. Agric.* **2013**, *3*, 61–68.
- Wang, F.J.; Xu, J.; Zhao, C.L. A Brief Review on the Evolution of the Architectural Complex at the Head of Dujiangyan in Modern Times. *J. Archit. Hist.* **2025**, *6*, 92–107. <https://doi.org/10.12329/20969368.2025.02010>.
- Research Group of “Management Issues of Dujiangyan Water Conservancy Project”. Management Decoding of Dujiangyan’s Millennial Continuation: A Perspective of Major Project Sustainable Development. *Manag. World.* **2023**, *39*, 1–16. <https://doi.org/10.19744/j.cnki.11-1235/f.2023.0061>.
- Zhang, H.; Chen, X.; Wang, Y.Q. Contemporary Value of Dujiangyan Living Heritage: Transformation Mechanism and Realization Path. *J. Xihua Univ.* **2026**, *45*, 54–63. <https://doi.org/10.12189/j.issn.1672-8505.2026.02.006>.
- Central Academy of Meteorological Sciences (Ed.). *Atlas of Drought and Flood Distribution in China over the Past 500 Years*; Map Publishing House: Beijing, China, 1981.
- Zheng, J.Y.; Zhang, P.Y.; Zhou, Y.F. An Experiment on Establishing Historical Drought/Flood Index Series Using Drought/Flood County Events. *Geogr. Res.* **1993**, *12*, 1–9. <https://doi.org/10.11821/yj1993030001>.
- Chen, Y.X. A Methodological Review on the Quantitative Grading of Historical Flood and Drought Data: Taking the Atlas of Drought and Flood Distribution in China over the Past 500 Years as an Example. *J. Shanghai Jiaotong Univ. (Philos. Soc. Sci.)* **2020**, *28*, 107–115.
- Yuan, Y.; Shi, Y.; Zhang, L.; Dong, J.F.; Lu, R.; Xia, B.; Lin, Y.; Cai, D.P. Characteristics of Drought and Flood Evolution in Nanjing from 1470 to 2012. *Chin. J. Agrometeorol.* **2025**, *46*, 281–289. <https://doi.org/10.3969/j.issn.1000-6362.2025.03.001>.
- Zhang, S.; Jiang, Q.G.; Xi, J.; Gong, Y.D. Extraction of Paleochannel Information Based on H/ α Decomposition Principle: A Case Study of Western Songnen Plain. *J. Jilin Univ.* **2020**, *50*, 1905–1916. <https://doi.org/10.13278/j.cnki.jjuese.20200008>.
- Cavallo, C.; Sarno, L.; Papa, M.N.; Negro, G.; Vezza, P.; Ruello, G.; Gargiulo, M. Estimating dry bed periods in non-perennial rivers using Sentinel-2 satellite data. *J. Hydrol.* **2025**, *754*, 7007541. <https://doi.org/10.1016/j.jhydrol.2025.7007541>.
- Qi, Z.S.; Yao, S.M.; Zhu, Y.; Liu, X.Q. Research Progress of River and Lake Evolution in China Based on Remote Sensing Technology. *J. Yangtze River Sci. Res. Inst.* **2025**, *42*, 8–17. <https://doi.org/10.11988/ckyyb.20240586>.
- Annayat, W.; Sil, B.S. Assessing channel morphology and prediction of centerline channel migration of the barak river using geospatial techniques. *Bull. Eng. Geol. Environ.* **2020**, *79*. <https://doi.org/10.1007/s10064-020-01894-9>.

20. Schmidt, J.; Lindemann, S.; Geißler, F.; Hein, M.; Lohse, N.; Schmidt-Funke, J.; Hardt, M. Spatiotemporal dynamics of river channel patterns during the last 400 years south of Leipzig, Germany. *E&G Quat. Sci. J.* **2025**, *74*, 355–381.
21. Radu, A.; Comănescu, L. Historical Evolution and Future Trends of Riverbed Dynamics Under Anthropogenic Impact and Climatic Change: A Case Study of the Ialomița River (Romania). *Water* **2025**, *17*, 2151.
22. Choi, K.; Kim, D.; Jo, J. Morphodynamic evolution of the macrotidal sittaung river estuary, myanmar: tidal versus seasonal controls. *Mar. Geol.* **2020**, *430*, 106367. <https://doi.org/10.1016/j.margeo.2020.106367>.
23. Arefin, R.; Meshram, S.; Seker, D. River channel migration and land-use/land-cover change for padma river at Bangladesh: a RS- and GIS-based approach. *Int. J. Environ. Sci. Technol.* **2021**, *18*, 3109–3126. <https://doi.org/10.1007/s13762-020-03063-7>.
24. Ijaz, M.; Mahar, R.; Ansari, K.; Siyal, A.A.; Anjum, M.N. Integrated assessment of contemporary hydro-geomorphologic evolution of the indus river estuary, pakistan in context to regulated fluvial regimes. *Estuar. Coast. Shelf Sci.* **2020**, 106657. <https://doi.org/10.1016/j.ecss.2020.106657>.
25. Feng, G.H. (Ed.) *Minjiang Annals*; Sichuan Provincial Department of Water Resources and Electric Power: Chengdu, China, 1990.
26. Editorial Committee of Sichuan Water Resources Annals (Ed.). *Sichuan Water Resources Annals*; Sichuan Provincial Department of Water Resources and Electric Power: Chengdu, China, 1989; Volume 3.
27. Local Chronicles Compilation Committee of Dujiangyan City. *Dujiangyan City Annals*; Fangzhi Publishing House: Beijing, China, 2000.
28. Compilation Committee of Qionglai City Annals (Ed.) *Qionglai City Annals: 1986-2005*; Fangzhi Publishing House: Beijing, China, 2011.
29. Local Chronicles Compilation Committee of Pengshan District (Ed.) *Pengshan County Annals*; Sichuan Science and Technology Press: Chengdu, China, 1991.
30. Zhao, R.Z.; Yang, Q.J. Multi-Function Optimization of Dujiangyan Terminal Canal System Based on “Production-Living-Ecological” Space. *Jiangsu Agric. Sci.* **2021**, *49*, 152–158.
31. Pan, W.; Man, Z.M. A Gridding Reconstruction Method for Historical River Network Density in Large River Deltas: A Case Study of Qingpu District, Shanghai (1918–1978). *J. Chin. Hist. Geogr.* **2010**, *25*, 5–14.
32. Yan, F.F.; Man, Z.M.; Pan, W. From Small Polders to Garden Fields: Changes in River Network Density in Shanghai over the Past Century. *J. Earth Environ.* **2014**, *5*, 425–433.
33. Wan, Z.W.; Shao, H.Y.; Liao, F.Q.; Jia, Y.L.; Jiang, M.X. Full-Element Reconstruction of County-Level Land Use in the Republic of China Period Based on 1:50,000 Topographic Maps: A Case Study of Qingjiang County, Jiangxi Province. *J. Chin. Hist. Geogr.* **2020**, *35*, 32–42.
34. Feng, Y.Y.; Hu, M.C.; Tan, X.Z.; Liu, B.J. Historical Land Use Reconstruction and Spatiotemporal Evolution Analysis Based on 1:50,000 Topographic Maps: A Case Study of the Meijiang River Basin. *J. Sun Yat-Sen. Univ.* **2023**, *62*, 104–112. <https://doi.org/10.13471/j.cnki.acta.snus.2022D031>.
35. Stachowicz, M.; Venegas-Cordero, N.; Ghezelayagh, P. Two centuries of changes-revision of the hydrography of the Biebrza Valley, its transformation and probable ecohydrological challenges. *Ecohydrol. Hydrobiol.* **2024**, *24*, 78–90. <https://doi.org/10.1016/j.ecohyd.2023.08.008>.
36. Xie, R.X.; Luo, Y.C. *Chongqing County Annals*, Lead print ed.; Changfu Company: Chengdu, China, 1926 (Minguo 15).
37. Wang, M.X.; Guo, Q.L. *Meishan County Annals*, Lithographic ed.; Hanwen Lithographic Press: Meishan, China, 1923 (Minguo 12).
38. Strahler, A.N. Hypsometric analysis of erosional topography. *Geol. Soc. Am. Bull.* **1952**, *63*, 1117–1142. [https://doi.org/10.1130/0016-7606\(1952\)63\[1117:HAOET\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1952)63[1117:HAOET]2.0.CO;2).
39. Li, J.R.; Li, S.C.; Liu, Y.T.; Zhang, X. Reconstruction of Irrigated Cropland Scale Change in the Central Plains Agricultural Region of China during the Historical Period: A Case Study of Northern Anyang City, Henan Province. *Prog. Geogr.* **2025**, *44*, 853–865.
40. Gao, F.; Tan, X.B.; Zhou, C.; Bian, S.; Shi, F. Eastward drainage-divide migrations driven by the spatial variations in precipitation and tectonic uplift contribute to the formation of the Parallel Rivers in the Hengduan Mountains, Southeastern Tibet. *Geomorphology* **2025**, 468, 109513. <https://doi.org/10.1016/j.geomorph.2024.109513>.
41. Zheng, J.Y.; Wen, Y.J.; Fang, X.Q. Some Characteristics of Climate and Land Cover Changes in the Middle and Lower Reaches of the Yellow River over the Past 2000 Years. *Resour. Sci.* **2020**, *42*, 3–19. <https://doi.org/10.18402/resci.2020.01.01>.
42. Wei, B.J.; Hou, Z.F.; Chen, S.Y.; Meng, J.; Fu, M.; Yang, L.; Liu, X.; Liu, J.; Chen, Y.; Yi, Y. Grain Size Characteristics of Sediments in Daye Marsh in the Lower Yellow River and Their Indication of Environmental Evolution. *Mar. Geol. Quat. Geol.* **2019**, *39*, 151–161. <https://doi.org/10.16562/j.cnki.0256-1492.2018080301>.

43. Liu, B.T.; Man, Z.M. Climate Fluctuations in the Lower Yangtze River Region during the Ming Dynasty Inferred from the Growing Period of Winter Wheat. *J. Chin. Hist. Geogr.* **2013**, *28*, 18–27.
44. Sun, E.; Lin, K.E.; Tseng, W.L.; Wang, P.K.; Huang, H.-S. Reconstructing East Asian Temperatures from 1368 to 1911 Using Historical Documents, Climate Models, and Data Assimilation. *arXiv* **2024**. <https://doi.org/10.48550/arXiv.2410.21790>.
45. Liu, J.; Chen, X.; Hans von, S.; Eduardo, Z.; Wang, S. Comparison of Climate Simulation and Reconstruction Data in China over the Past 500 Years. *Adv. Earth Sci.* **2006**, *21*, 401. <https://doi.org/10.11867/j.issn.1001-8166.2006.04.0401>.
46. Yang, J.H.; Zhang, Q.; Wang, J.S.; Yao, Y.B.; Shang, J.L.. Understanding Drought/Flood Variations and Their Extreme and Persistent Characteristics in Southwest China in Recent 60 Years. *Sci. Geogr. Sin.* **2015**, *35*, 1333–1340. <https://doi.org/10.13249/j.cnki.sgs.2015.010.1333>.
47. Li, S.P. *History of Sichuan Population*; Sichuan University Press: Chengdu, China, 1987.
48. Cao, S.J. Population of Sichuan Prefectures in the Mid-Qing Dynasty: Based on Data of 1812. *Res. Chin. Econ. Hist.* **2003**, *1*, 72–84.
49. Skinner, G.W. Population of Sichuan in the 19th Century—Lessons from Unverified Data. In *Urban Research in Late Imperial China: The Skinner Model*; Wang, X., et al., Trans.; Liaoning Education Press: Shenyang, China, 1991; pp. 232–301.
50. Wang, D. *Stepping Out of a Closed World: A Social Study of the Upper Yangtze Region (1644–1911)*; Zhonghua Book Company: Beijing, China, 2001.
51. Chang, M.; Yang, F.C.; Tan, G.H. Volume 23, Dikes and Weirs. In *Sichuan General Annals*, Block-printed ed.; Chengdu, China, 1816 (Jiaqing 21).
52. Ye, D.Q.; Luo, J.S. *Guan County Annals*, Lead print ed.; Meilili Printing Company: Chengdu, China, 1933 (Minguo 22).
53. Zhang, J.; Zeng, X.C. *Wenjiang County Annals*, Block-printed ed.; Wenjiang County Gazetteer Office: Wenjiang, China, 1921 (Minguo 10).
54. Zhou, X.; Liu, X.C. *Revised Pengshan County Annals*, Lead print ed.; Xianguang Printing Factory: Pengshan, China, 1944 (Minguo 33).
55. Ding, R.B.; Gu, Y.F.; Wei, D.N.; Xie, P.Y. *Chongqing Prefecture Annals*, Block-printed ed.; Chongqing (now Chongzhou), China, 1813 (Jiaqing 18).
56. Shen, E.P.; Hu, L.; Xu, D.Y. *Expanded Chongqing Prefecture Annals*, Block-printed ed.; Chongqing (now Chongzhou), China, 1884 (Guangxu 10).
57. Ji, Z.Y. *Pujiang County Annals*, Block-printed ed.; Pujiang, China, 1784 (Qianlong 49).
58. Sun, Q.S.; Xie, H.; Xu, Y.S. *Pujiang County Annals*, Block-printed ed.; Pujiang, China, 1878 (Guangxu 4).
59. Liu, X.; Ning, X. *Qionglai County Annals*, Lead print ed.; Qionglai County Gazetteer Office: Qionglai, China, 1922 (Minguo 11).
60. Guo, S.F.; Wen, B.C. Volume 9, Water Conservancy, In *Qingshen County Annals*, Block-printed ed.; Qingshen, China, 1877 (Guangxu 3).
61. Tang, S.P.; Huang, R.; Xie, S.X. Volume 5, Constructions, In *Leshan County Annals*, Lead print ed.; Meilili Printing Company: Chengdu, China, 1934 (Minguo 23).
62. Tu, C.F.; Wang, C.N. Volume 8, Water Conservancy, In *Meizhou Subordinate Annals*, Block-printed ed.; Meizhou, China, 1812 (Jiaqing 17).
63. Editorial Committee of Sichuan Water Resources Annals (Ed.) *Sichuan Water Resources Annals*; Sichuan Provincial Department of Water Resources and Electric Power: Chengdu, China, 1989; Volume 6.
64. Yu, X.S.; Meng, H.W.; Huang, L.P.; Sun, Q.; Wang, M.; Zhang, H.; Shan, C. Environmental Changes in the Yangzonghai Lake Basin of Central Yunnan over the Past 1200 Years. *Chin. J. Ecol.* **2020**, *39*, 1896–1910. <https://doi.org/10.13292/j.1000-4890.202006.001>.
65. Yu, H.; Wang, X.; Ji, M.; Zhang, S.; Pan, G.; Guo, L.; Cui, L.; Ma, X.; Li, W.; Li, D. Tetraether-based temperature record from Lake Xingyun in southwestern China since late MIS3 and implication for regional differences in temperature reconstruction. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2025**, *675*, 113122. <https://doi.org/10.1016/j.palaeo.2025.113122>.
66. Wang, R.S.; Wang, S.W. Reconstruction of Winter Temperatures in Eastern China over the Past 500 Years. *Acta Meteorol. Sin.* **1990**, *48*, 180–189. <https://doi.org/10.11676/qxxb1990.022>.
67. Zheng, J.; Liu, Y.; Hao, Z.; Zhang, X.; Ma, X.; Liu, H.; Ge, Q. Winter temperatures of southern China reconstructed from phenological cold/warm events recorded in historical documents over the past 500 years. *Quat. Int.* **2018**, *525*, 42–47.
68. Sichuan Provincial Archives. *Various Statistics of Sichuan Province during the War of Resistance Against Japan*; Southwest Jiaotong University Press: Chengdu, China, 2010.

69. Lan, Y.; Huang, Q.S. Huguang Filling Sichuan. In *and Qing Dynasty Sichuan Society*; Southwest China Normal University Press: Chongqing, China, 2009.
70. Jiang, W.J.; Zhao, K.; Chen, S.T.; Wang, Y.J.; Cheng, H.; Ning, Y.F. Stalagmite Record of Decadal-Scale Asian Monsoon Variation during the Little Ice Age from Heizhugou Cave, Sichuan. *Quat. Sci.* **2017**, *37*, 118–129. <https://doi.org/10.11928/j.issn.1001-7410.2017.01.11>.
71. Zhao, B.; Cui, Y.F.; Kong, X.G.; Zhao, K.; Wang, Y.J. Hydrological Climate Change in Southwest China over the Past 800 Years and Its Dynamic Mechanism. *Geol. J. China Univ.* **2024**, *30*, 747–755. <https://doi.org/10.16108/j.issn.1006-7493.2023063>.
72. Liu, B.; Sheng, E.G.; Yu, K.K.; Zhou, K.E.; Lan, J.H. Variations in monsoon precipitation over southwest China during the last 1500 years and possible driving forces. *Sci. China Earth Sci.* **2022**, *65*, 949–965. <https://doi.org/10.1007/s11430-021-9888-y>.
73. Shen, Z.F. The Limits of Water Conservancy: An Investigation of Irrigation Development and Environmental Change in the Dabie Mountains during the Historical Period. *Agric. Hist. China.* **2017**, *36*, 92–101.
74. Dai, J.B.; Sun, B. *Chinese Environmental History: Ming and Qing Volumes*; Higher Education Press: Beijing, China, 2021.
75. Zhang, L. Changing with the Yellow River: an environmental history of hebei, 1048-1128. *Harv. J. Asiat. Stud.* **2009**, *69*, 1–36. <https://doi.org/10.1353/jas.0.0001>.
76. Zhou, Q. A Preliminary Study on the Consequences of Inlandization in Yunnan during the Qing Dynasty: A Focus on Water Conservancy Projects. *Jiangnan Trib.* **2008**, 75–82. <https://doi.org/10.3969/j.issn.1003-854X.2008.03.016>.

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