

<https://doi.org/10.1038/s40494-025-02127-6>

# Spatial form and formation process of irrigation district cultural landscapes: the Songgu irrigation District, Zhejiang, China

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Considering the threat of urbanization, exploring the multilevel spatial characteristics of irrigation district cultural landscapes (IDCLs) is crucial for their sustainable conservation. This study employs a multiscale framework and interdisciplinary approach to reveal the spatial pattern characteristics of the Songgu IDCL, a World Heritage Irrigation Structure in China. Two typical irrigation district unit types, four farmland texture types, and three settlement distribution types are identified, and the water–society management systems are clarified. The results indicate that IDCLs are multilayered systems driven primarily by their irrigation infrastructure. Water–society management maintains and reconfigures spatial patterns by regulating resource allocation and resolving conflicts of interest. These findings deepen our understanding of the spatial characteristics and evolutionary patterns of IDCLs, thereby providing a scientific basis for their living conservation and value regeneration.

Cultural landscapes embody the interaction between nature and human culture, and their preservation has become a critical issue for achieving the United Nations Sustainable Development Goals (SDG 11.4)<sup>1</sup>. These landscapes are classified by the World Heritage Committee into three categories: designed, organically evolved, and associative<sup>2</sup>. Organic evolutionary landscapes are characterized by “continuous adaptation to natural processes”. The spatial forms of these landscapes provide insights into how humans gradually adapt to local natural environments and create habitable space. Irrigated district cultural landscapes (IDCLs) are an important subtype of organically evolved landscapes. To meet water demands for irrigation and other purposes, IDCLs have been transformed by anthropogenic activities, particularly through the construction of irrigation infrastructure, thus resulting in the alteration of regional spatial patterns. These landscapes are characterized by, for example, rivers, riverine landforms, irrigation infrastructure and water management techniques<sup>3</sup>. IDCLs can be categorized into three types according to the spatial distribution of their irrigation infrastructure: surface water irrigation, groundwater irrigation<sup>4</sup>, and composite irrigation. These differences reflect human adaptive strategies in diverse natural environments, which form multiple types of IDCLs.

IDCL irrigation infrastructures have become a cornerstone for the livelihood of farmers<sup>5</sup> and represent a substantial part of the tangible and intangible cultural heritage of entire regions<sup>6</sup>. The great value of these infrastructures is documented through the recognition of multiple irrigation infrastructures as UNESCO World Heritage sites. As stated by ICOMOS-IFLA in Principles Concerning Rural Landscapes as Heritage, IDCLs, as typical natural-social composite systems<sup>7,8</sup>, derive their value from not only the irrigation infrastructure but also the spatial characteristics and historical

stratification of the natural environment, agricultural patterns, and community organizations<sup>9–11</sup>. These elements collectively shape the specific regional characteristics of IDCLs<sup>12</sup>. However, in the context of rapid urbanization, the integrity of IDCLs is easily compromised<sup>13</sup>, for example, through the abandonment of traditional irrigation infrastructures and the erosion of water rights. One fundamental cause of these issues is the lack of recognition of the overall value of IDCLs. Therefore, exploring the spatial characteristics and historical stratification of IDCLs is important for their conservation and management.

In recent years, cultural landscapes have attracted sustained scholarly attention<sup>14,15</sup>. However, studies on IDCLs have focused largely on individual hydraulic projects, such as canals<sup>16</sup> and weirs, with limited efforts to examine IDCLs as integrated systems. Existing research includes multidisciplinary research. Hydraulic science focuses on hydraulic structures and water allocation<sup>17–19</sup>, whereas agricultural science emphasizes agricultural engineering and economics<sup>20,21</sup>. In contrast, human settlement studies draw on GIS and historical maps to quantify spatial patterns<sup>12</sup>. By examining various aspects, such as canal–terrain adaptation<sup>22</sup> and the symbiotic relationships between farmland and water infrastructure<sup>23,24</sup>, researchers have revealed the spatiotemporal evolution of the characteristics of IDCLs<sup>25,26</sup>. These studies provide a foundation for understanding the resilience and value of IDCLs as “living cultural carriers”<sup>27</sup> and nature–society systems. However, findings from cases such as the Zhang-ye IDCL indicate that urbanization and agricultural modernization fragment IDCL spatial characteristics<sup>16</sup>, thereby underscoring their vulnerability. Current water–society research has analyzed IDCL governance practices through historical analysis and structured interviews while considering aspects such as water rights<sup>28</sup>, self-

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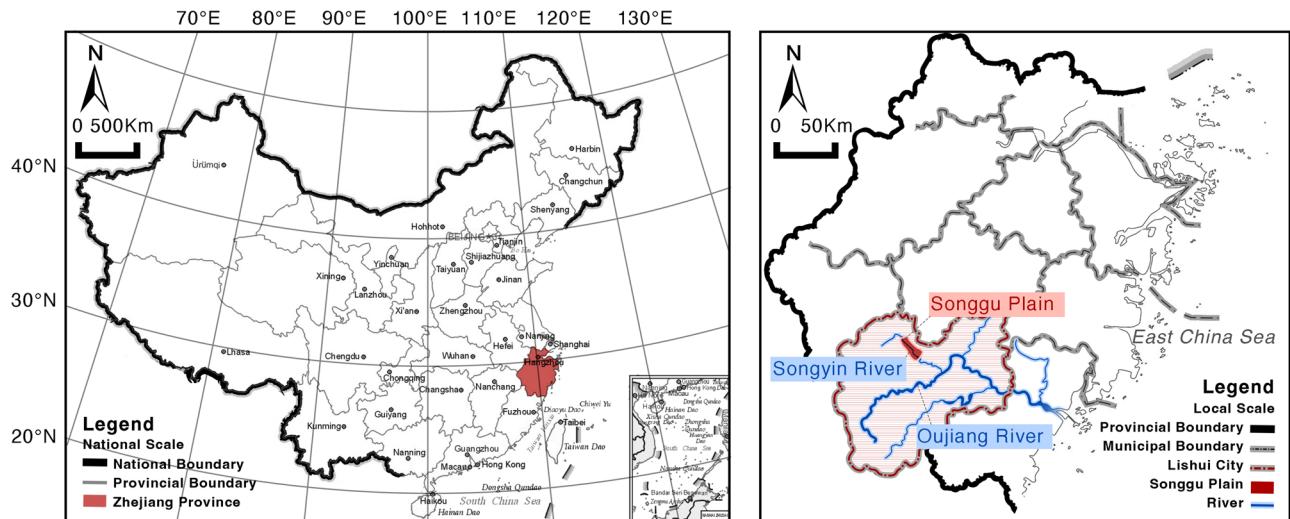


Fig. 1 | National Scale and Local Scale. Location of the Songgu IDCL.

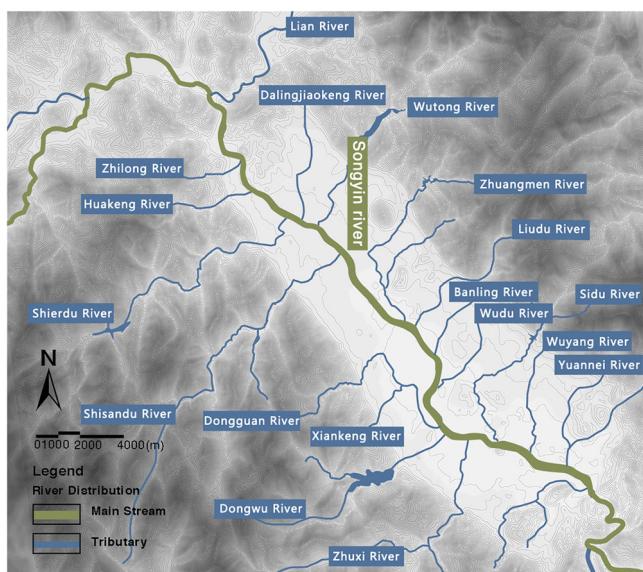


Fig. 2 | River distribution. Distribution of river in the Songgu IDCL.

governance<sup>29</sup>, policy intervention<sup>30</sup>, property rights<sup>31</sup>, and population migration<sup>32</sup>. These studies highlight the significance of public participation<sup>33</sup> in preserving IDCLs<sup>34</sup>. However, regarding conservation, the proposed methods include optimizing irrigation efficiency by using the SWAT model<sup>33</sup>, monitoring threat dynamics through remote sensing<sup>24</sup>, and tourism revitalization<sup>27</sup>.

In summary, while existing research has generated rich interdisciplinary discussions on IDCLs, systematic spatial studies are still lacking. The main gaps in current research include the following: spatial studies often focus on a single scale or element, such as water conservancy projects or settlement distributions, and neglect the multilayered systemic characteristics and integrated nature of landscapes; studies have primarily focused on single irrigation district units (IDUs), which limits the ability to perform cross-district comparisons that reveal spatial differences and systemic commonalities; research tends to emphasize either the material spatial dimension or the social governance dimension and overlook the interactive social-spatial characteristics<sup>9</sup>; and current conservation strategies focus primarily on maintaining irrigation functions or promoting tourism revitalization and fail to provide a systematic response to the layered

evolutionary characteristics and regional spatial value of IDCLs as organically evolved landscapes.

The Songgu IDCL, located in Songyang County, Zhejiang Province, was added to the World Heritage Irrigation Structures List in 2022<sup>35</sup> and has rich cultural connotations and significant research value. For 6,000 to 7,000 years, local residents have engaged in water conservancy activities that rely on mountain streams and rivers that have gradually formed the Songgu IDCL, which comprises numerous irrigation units. As a typical group of irrigation districts developed by China's mountain streams in small- to medium-sized watersheds, the Songgu IDCL serves as an ideal case study for analyzing the spatial characteristics of multiunit irrigation districts. However, the characteristic cultural landscape features of the Songgu IDCL have been significantly impacted by urbanization since the 1980s. To effectively preserve the cultural landscape characteristics of the irrigation area, further examining the spatial features of the Songgu IDCL prior to urbanization is particularly important.

Therefore, this study focuses on the Songgu IDCL from the 1960s to the 1980s before urbanization. An innovative three-level spatial framework is constructed: “the integrated IDCL system, the irrigation district cluster (IDC), and the irrigation district unit (IDU)”. The IDCL system is divided into five layers: the natural environment, the irrigation infrastructure, the agricultural system, the settlement system, and the water-social system. By using historical records, GIS spatial analysis, and morphological typology, this study investigates the spatial distribution and morphological characteristics of these layers at different scales, thereby revealing their coupling mechanisms. Our research empirically contributes to international IDCL research and advances the refinement of research on specific IDCL types at a specific regional scale. Furthermore, we offer theoretical support for identifying the value of IDCLs and preserving and managing them.

## Methods

### Research area

The Songgu IDCL is in the Songgu plain of Songyang County, Zhejiang Province, China (Fig. 1). The basin is surrounded by mountains over 1000 m, with elevations between 8 and 150 m and an area of approximately 17,500 hectares. The Songyin River flows from northwest to southeast through the Songgu Plain, thereby serving as the main trunk of the irrigation area. Numerous mountain streams originating from the surrounding hills form tributaries, thereby creating a fishbone-like structure that provides sufficient water resources (Fig. 2).

The Songgu IDCL comprises 18 primary tributaries, which irrigate an area of approximately 4,000 hectares. The Songgu IDCL comprises nearly one hundred IDUs of varying sizes, ranging from 1 to 600 hectares (the

**Table 1 | Classification of IDCL layers**

IDCL Layers	Constituent Elements	Function and Supporting Relationships	Evolutionary Rate
Natural Systems	landforms, water bodies	Provide environmental foundation and constraints	Long-term stability
Irrigation infrastructure Systems	Weirs, canals, ponds	Guide and control water resources; are constrained by natural systems	Century-scale persistence
Agricultural Systems	Field units	Support production functions; rely on irrigation to support its land use	Moderate
Settlement Systems	Settlements	Support habitation and social organization; are formed according to agricultural and irrigation systems	Relatively rapid
Water-Society	Organizational system, water-rights system	An intangible layer that constrains water allocation and use	Fast

ancient Chinese measurement unit “mu” equals approximately 666.667 square meters, with 100 mu equaling approximately 6.7 hectares). The Songgu IDCL became a developed agricultural region in China as early as the Ming and Qing dynasties. Paddy fields are primarily used for growing cultivated rice, whereas dry fields are primarily used for growing wheat, corn, and other crops.

### Research framework

This study presents a comprehensive methodological framework for analyzing cultural landscapes that integrates quantitative and qualitative approaches<sup>36</sup>. At the overall scale, spatial analysis and morphological typology methods are employed to reveal the spatial patterns and morphological characteristics of the Songgu IDCL landscape layers. For the IDC scale, 11 large-scale IDUs were selected according to data completeness and case representativeness. Using standard deviation ellipse (SDE) and ordinary least squares (OLS) regression models, we analyzed the spatial and scale coupling relationships among the different landscape layers. At the IDU scale, the Fangxi Weir IDU (F\_IDU) was selected for this case study because of its comprehensive data and significant representativeness. This detailed investigation revealed the spatial distribution and influence relationships among landscape layers within the IDU, thereby deepening the comprehensive understanding of IDCLs.

### Classification of IDCL layers

Cultural landscape studies generally emphasize the multilayered composition of cultural landscapes and the characteristics of connections between components<sup>37–40</sup>. Drawing on methods such as historical ecology and landscape biography, this study regards IDCLs as layered historical processes, thus highlighting their multilayered spatial characteristics emerging through long-term evolution<sup>36</sup>. Existing research has expanded the classification of landscape layers from the earliest layers of water conservancy and agriculture to multiple layers that include the natural environment, land use, and settlement patterns<sup>10,11</sup>. Furthermore, the “landscape pyramid” model and related research reveal differences in evolutionary rates across different landscape layers. The relatively stable lower layers provide support for the upper layers<sup>37,41</sup>, whereas the upper layers are more strongly influenced by anthropogenic activities and management<sup>42</sup>. These findings provide theoretical support for the historical evolution of IDCLs and the layer associations within them. Therefore, in this study, the material space of IDCLs is divided into four layers from bottom to top: natural systems, irrigation infrastructure systems, agricultural systems, and settlement systems. Table 1 shows the elements, functions, and supporting relationships among layers.

Furthermore, this study introduces the concept of the “water society”<sup>43</sup>. Originating from geography, this concept recognizes water as an element that combines social and hydrological dimensions<sup>44</sup>. The processes of water allocation and utilization create management forms characterized by regional cultural features<sup>45</sup>, which can be regarded as intangible cultural elements<sup>6,46</sup>. Building on this understanding and drawing upon relevant research on organic evolutionary landscape governance<sup>42</sup> and socio-ecological systems (SES) theory<sup>47,48</sup>, this study adopts the water society as an independent social layer. This layer encompasses elements such as

construction schemes and water rights management<sup>49</sup>. The change rate of this layer exceeds that of material layers and it is typically at the top layer<sup>42</sup>.

Ultimately, this study constructed an analysis framework supported by interdisciplinary theory to comprehensively describe the characteristics of IDCLs (Table 1). This framework is applicable to cultural landscape studies dominated by water conservancy under similar scales and data conditions. However, detailed indicators and elements still depend on regional characteristics, thus necessitating adjustment for local diversity during cross-regional comparisons and promotion.

Natural systems provide landforms and hydrological foundations upon which the network of the irrigation infrastructure system is constructed. Agricultural systems rely on irrigation to support land use, and settlement systems are formed according to production organization and water resource distribution. This layered relationship not only clarifies the functional differences among factors but also clearly reveals the historical evolutionary logic of IDCLs.

### Data source and processing

This study used multisource data from the 1960s to the 1980s. A 30-meter resolution digital elevation model (DEM) was sourced from the Geospatial Data Cloud (2015, <https://www.gscloud.cn/home>). Given the limited topographic changes, this version effectively represents the topographic conditions from the 1960s to the 1980s. Slope data were generated from the DEM using ArcGIS. Historical imagery from 1968 was obtained from the U.S. Geological Survey (<https://earthexplorer.usgs.gov>) at a resolution of 2 meters. Contemporary remote sensing imagery was obtained from the National Geographic Information Platform. Data on farmland areas and settlements for each IDU were collected from historical and modern records, including the Songyang County Annals from the Qing and Ming dynasties, the Songyang Water Conservancy Annals (2006), and the Songyang Place Name Annals (1987). Population data were sourced from 1960s census records held by the Songyang Archives. Historical materials related to the water-society system, including water conservancy archives and stele inscriptions from the Ming and Qing dynasties, such as the Fangxi Weir Water Period Stele (1690) and the Fangxi Weir Notice (1824), were also sourced from the Songyang Archives.

Research samples selection followed the principles of data availability, reliability, and representativeness. At the overall scale, only IDUs with irrigated areas larger than 13.3 hectares (200 mu) were analyzed, thereby excluding smaller IDUs with incomplete data or limited spatial verifiability. At the IDC scale, we selected typical large IDUs covering more than 66.7 hectares (1000 mu) with sufficient data. These IDUs feature mature structures and represent both IDU types, thereby accurately reflecting the core characteristics of the Songgu IDCL. At the IDU scale, the study focused on F\_IDU, the largest and most thoroughly documented unit, to enable in-depth analysis at the mechanism level.

Using modern remote sensing imagery as the spatial reference, this study uses historical satellite imagery from 1968, which has been georeferenced and spatially corrected, for landscape feature identification and vectorization. All point, line, and polygon features were drawn in ArcGIS through point-to-point connections and backtracking. To ensure data

reliability and reproducibility, all operations were independently performed and cross-validated by two researchers. In the irrigation infrastructure system, weirs were first located by identifying their streams from historical hydraulic records. Afterward, the project location on the corresponding stream within historical imagery was identified and crosschecked with modern imagery and field surveys. Canal centerlines are extracted from historical imagery by referencing weir locations and identifying distinct canal systems, which is cross-verified with historical maps and records. Minor canals were not individually vectorized. Settlement data were derived from place name gazetteers and history maps. After performing geographic registration and spatial correction, the researchers imported the data into ArcGIS to obtain settlement locations. Additionally, descriptive attributes (distribution type, IDU affiliation, etc.) were assigned to settlements for spatial analysis and visualization. IDU boundaries were primarily derived from hydrological gazetteers, place name gazetteers, and historical imagery and cross-validated with documented area data. These boundaries represent cultivated land areas.

An analysis of farmland morphology types was not incorporated into the GIS database. Two researchers independently extracted field block samples from historical imagery by using morphological typology methods, summarized their morphological characteristics, classified them, and ultimately produced a texture map.

### Analytical methods

**Spatial analysis methods.** Spatial analysis tools in ArcGIS were used to measure and visualize the historical geographic data of the Songgu IDCL. Kernel density analysis<sup>50</sup>, spatial autocorrelation, local Moran's I index, and hotspot analysis<sup>51</sup> were employed to reveal the spatial distribution density and clustering characteristics of elements. At the overall scale, the analysis focused on weirs and villages; at the IDU scale, the analysis focused on canal networks and villages. Standard deviation ellipses (SDE)<sup>52</sup> were used to analyze the spatial distribution relationships, including direction and extent, among the irrigation infrastructure, agricultural, and settlement systems. The calculation formulas and geographical significance of these methods are shown in Table 2.

**Morphological typology methods.** The mapping method<sup>53</sup> was used to explore the morphological characteristics and evolutionary logic of the Songgu IDCL. Mapping serves as a tool for measuring and describing landscape elements, offering an interpretation and representation of historical and current conditions based on site surveys and data organization by researchers. The specific steps are as follows: (1) Morphological extraction: essential forms and patterns of landscape elements are identified based on their morphological structures and characteristics. Satellite imagery and maps were used as primary sources and were supplemented by field surveys and archival documents; (2) Typology induction: similarities and differences in spatial scale, planar form, and structural organization among landscape element patterns are compared, and principles for defining morphological types are summarized; and (3) Evolutionary logic: the logical relationships of morphological formation and transformation are interpreted using evolutionary perspectives from typology<sup>54</sup>.

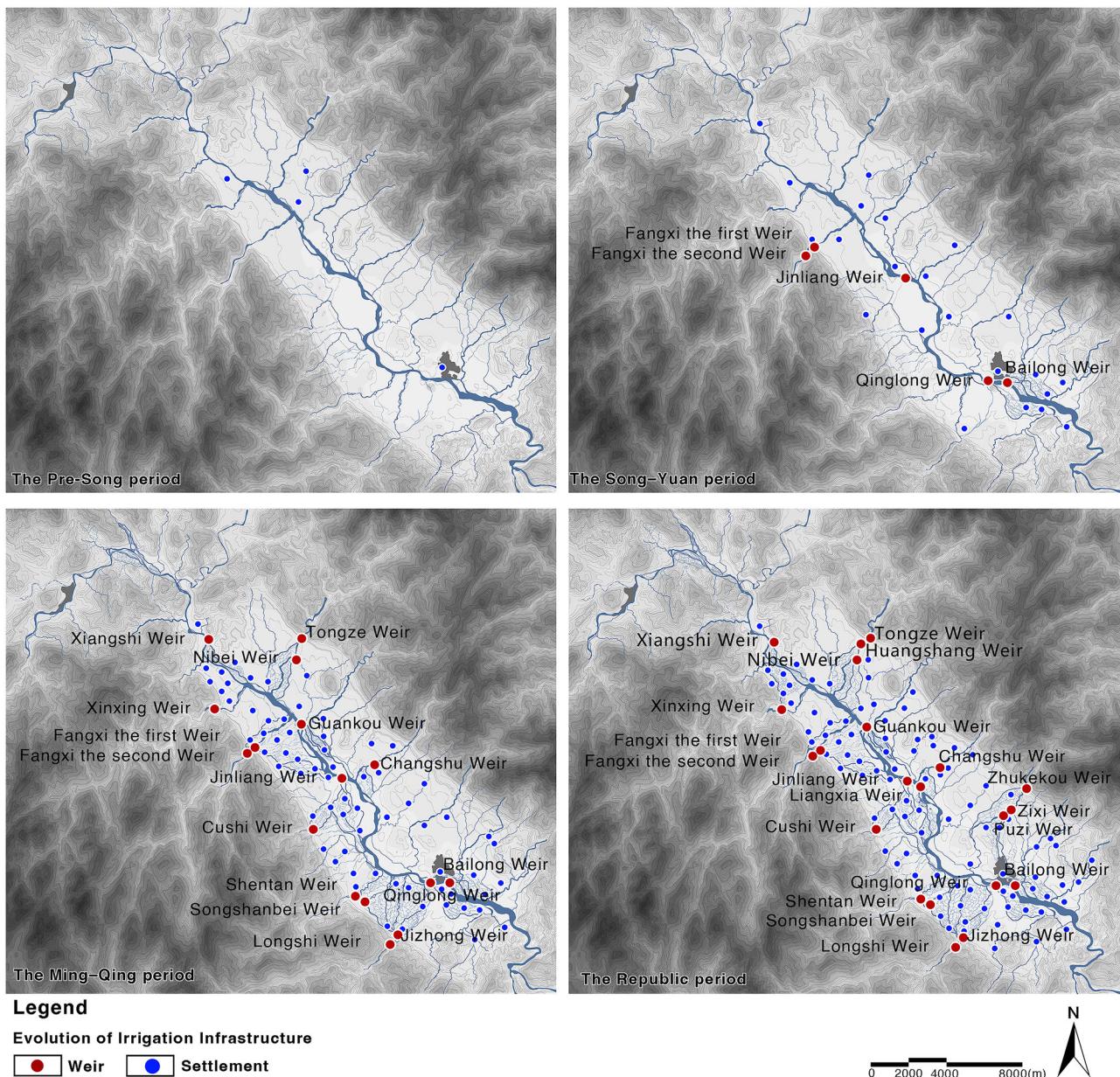
**Correlation analysis and OLS regression model.** Pearson correlation analysis was used to preliminarily assess linear relationships among variables across the three layers (the irrigation infrastructure, agricultural, and settlement systems) within each IDU<sup>55</sup>. Correlation coefficients range from -1 to 1. The absolute value indicates the strength of the relationship, and the sign indicates the direction (positive or negative).

Ordinary least squares (OLS) regression, a classical statistical model, was employed to quantify the linear influence of independent variables on dependent variables. The study used OLS to explore the impact of the irrigation infrastructure systems on the agricultural and settlement systems. All analyses were conducted using SPSS.

To quantify scale relationships among the three layers, the following variables were selected: main canal length ( $X_1$ ) and main canal density ( $X_2$ )

**Table 2 | Spatial analysis methods and their geographic interpretation**

Method	Formula	Explanation	Geographic Meaning	Purpose
Kernel Density	$\lambda(x) = \frac{1}{mh} \sum_{i=1}^n k\left(\frac{x-x_i}{h}\right)$	$k$ is the kernel function; $h$ is the search radius; $(x-x_i)$ represents the distance from the estimation point $x$ to the feature point $x_i$ .	Higher $\lambda(x)$ values indicate higher concentration of features.	To evaluate the dispersion or clustering characteristics of landscape elements.
Spatial Autocorrelation	$I = Z_i + \sum_{j=1}^n W_{ij}Z_j$	$I$ is Moran's $I$ ; $Z_i$ and $Z_j$ are the standardized values of the observed values for spatial units $i$ and $j$ ; $W_{ij}$ is the spatial weight.	Moran's $I$ ranges from -1 to 1. Positive values indicate positive spatial autocorrelation (clustering of high or low values), negative values indicate negative spatial autocorrelation (dispersed patterns), and values near zero indicate random spatial distribution.	To reveal the spatial correlation of landscape elements with neighboring elements.
Local Moran's I	$I_i = \frac{(x_i - \bar{x}) \sum_{j=1}^n w_{ij}(x_j - \bar{x})}{\sum_{j=1}^n (x_j - \bar{x})^2}$	$x_i$ and $x_j$ are the attribute values of features $i$ and $j$ ; $\bar{x}$ is the mean of the attribute values, and $w_{ij}$ is the spatial weight between features $i$ and $j$ .	Visualizes local clustering patterns of landscape elements.	To identify areas of local spatial clustering in landscape elements.
Getis-Ord Gi* Analysis	$G_i^* = \frac{\sum_{j=1}^n w_{ij}x_j - \bar{x} \sum_{j=1}^n w_{ij}}{S \sqrt{\left(\sum_{j=1}^n w_{ij}^2\right) \left(\sum_{j=1}^n w_{ij}\right)}}$	$x_j$ is the attribute value at location $j$ , $w_{ij}$ is the spatial weight between locations $i$ and $j$ , $\bar{x}$ is the mean of the attribute values, and $S$ is the standard deviation of the attribute values.	High $Gi^*$ values indicate statistically significant hotspots, whereas low values indicate cold spots.*	To visualize the local hotspots and coldspots distribution of landscape elements.
Standard Deviational Ellipse (SDE)	$SDE_y = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n}}$	$x_i$ and $y_i$ are the spatial coordinates of the research features.	The long axis and short axis indicate the primary and secondary directional trends of feature distribution. Their lengths represent the degree of dispersion of features along the main and secondary trends relative to the centroid.	To reveal and compare the directional trend and extent of spatial distribution of landscape elements.



**Fig. 3 | Evolution of irrigation infrastructure.** Evolution of irrigation infrastructure of the Songgu IDCL.

for the irrigation infrastructure system, reflecting the scale of IDU irrigation; farmland area ( $Y_1$ ) for the agricultural system, reflecting the scale of cultivation; and settlement population ( $Y_2$ ) for the settlement system, reflecting the settlement scale and development level of IDUs.

## Results

### Evolution of irrigation infrastructure

According to the Qing and Republic-era Songyang Gazetteers and the 1987 Songyang place name records, the settlement history of the Songgu IDCL can be traced back six to seven millennia. The Songgu IDCL irrigation system began developing during the Tang–Song period (9<sup>th</sup>–13<sup>th</sup> centuries) and matured during the Ming–Qing period (14<sup>th</sup>–19<sup>th</sup> centuries); thus, this system is a paradigmatic example of ancient small- to medium-sized watershed irrigation engineering in China. The evolution of the Songgu IDCL can be divided into four stages (Fig. 3):

**The Pre-Song period:** The irrigation infrastructure had not yet emerged. As shown in Fig. 3a, only four settlements were sparsely

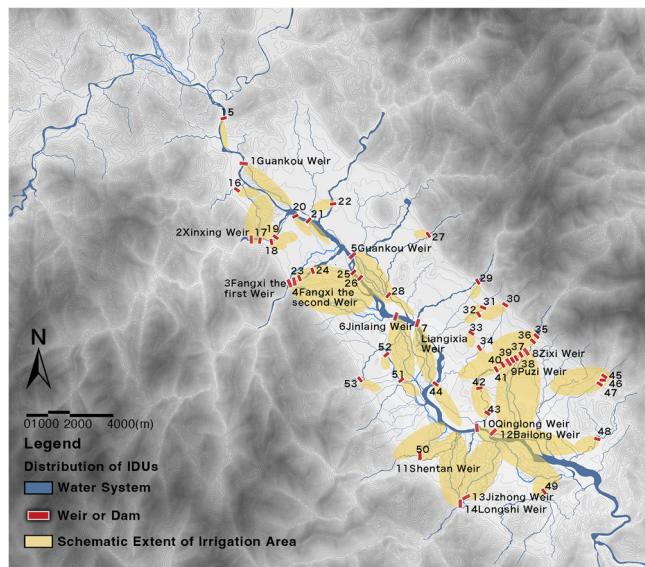
distributed along Songyin Creek. The extreme variability in river flow, coupled with frequent droughts and floods, constrained settlement development during this period.

**The Song–Yuan period:** The irrigation infrastructure was in an early stage of development. The construction of five large-scale weirs, each with more than 1000 mu of irrigation, is illustrated in Fig. 3b. These include the Qinglong and the Fangxi weirs (which were built during the Song period) and the Jinliang and the Bailong weirs (which were established during the Yuan period). Large official ponds were also excavated during this period. Settlements increased to 22, including the villages of Song-era Wayao Tou, Xucheng, and Jinliang (the latter of which gradually flourished during the Yuan period).

**The Ming–Qing period:** The irrigation infrastructure entered a phase of rapid expansion. In Fig. 3c, the number of large weirs increased to 16 (five of which have since disappeared), including seven constructed during the Qing period. In addition to extensive weir construction, water was diverted from the main canals into the branch and minor canals, thus resulting in the

**Table 3 | Statistics of weirs in the Songgu IDCL (2004 statistical data)**

	>1000 mu	200-1000 mu	100-200 mu	>100 mu	Total
Number Of Main Stream Weirs	6	7	4	--	17
Number Of Tributary Weirs	9	31	34	--	74
Total	15	38	38	--	91
Irrigated Area	2100	1300		800	4200

**Fig. 4 | Distribution of IDUs.** Distribution of IDUs in the Songgu IDCL (irrigation > 200 mu).

formation of a comprehensive irrigation network. The IDU flood control capacity improved, agricultural productivity increased, and settlements prospered accordingly.

The Republic period: The irrigation infrastructure reached a period of stable development. As shown in Fig. 3d, the number of large weirs increased to 21 (seven of which no longer exist), and the irrigation structure of the Songgu IDCL stabilized. In 1938 (Republic Year 27), storage pond projects began construction. These developments gradually formed the composite water system of interconnected ponds and canals that persists today.

### Composition of the Songgu IDCL

According to the Songyang Water Conservancy Records (2004) (Table 3), the Songgu IDCL encompasses approximately 4,000 ha of irrigated land and comprises nearly one hundred IDUs of varying sizes, ranging from 1 to 600 hectares (the ancient Chinese measurement unit “mu” equals approximately 666.667 square meters, with 100 mu equaling approximately 6.7 hectares). IDUs can be categorized into main-stream and tributary diversion units according to the location of the weirs. There are 17 main-stream IDUs, accounting for 19% of all units. Although relatively few, these units cover larger areas, typically exceeding 66.7 ha (1000 mu) per single-weir IDU, and the total area of this type of IDU represents nearly half of the entire irrigated area. Tributary IDUs totaled 74, thus accounting for 81% of the total. Their sizes ranged from 0.7 ha (10 mu) to 600 ha (9,000 mu), with 40 IDUs exceeding 13.3 ha. The approximate distribution of IDUs with irrigated areas larger than 13.3 ha is shown in Fig. 4.

### Irrigation infrastructure system

Each IDU possesses an independent and relatively complete irrigation system, which comprises a weir diversion system, a canal network system, and a pond-reservoir regulation system. The weir diversion system raises

water levels via weirs and incorporates sluice gates for water distribution, regulation, and drainage, thereby facilitating gravity-fed irrigation throughout the IDU<sup>56</sup>. The canal network system consists of main canals, branch canals, and minor canals. The pond-reservoir regulation system connects with the canal network to store floodwater, irrigate farmland, and supply domestic water.

Kernel density analysis was employed to investigate the spatial distribution characteristics of weirs (Fig. 5). The results indicate a “two-core, one-belt” spatially heterogeneous distribution pattern, with the two cores being the highly dense southeast zone ( $K = 8.33$ ) and the moderately dense northwest zone, which primarily comprise tributary weirs. The belt refers to the Songyin Creek density belt, which is formed mainly by main-stream weirs.

A global spatial autocorrelation analysis of weirs yielded a Moran’s I index value of 0.904355 ( $p = 0.00$ ) and a  $z$  value of 37.761111, which were significantly greater than 2.58. This indicates pronounced spatial clustering in the weir distribution. High-low clustering analysis revealed a  $z$  score of 35.909694 ( $p = 0.00$ ), thereby further confirming that weirs exhibit significant high-value clustering concentrated in specific areas.

Given the evidence of positive spatial autocorrelation and high-value clustering, local Moran’s I and Getis-Ord  $Gi^*$  were employed to further investigate the spatial clustering characteristics of weirs and dams. The results of spatial autocorrelation (Fig. 5b) reveal high-high (HH) clusters in the Fangxi and Zixi tributary weir areas and the mainstem regions, including the Guankou, Jinliang, and Qinglong weirs. These findings indicate that these areas serve as hotspots for weir distribution and are surrounded by other high-value regions. Hotspot analysis (Fig. 5c) further indicates that extensive hotspot areas are concentrated in the foothills northwest and southeast of the IDCL, which are formed by tributary weirs. Hotspots associated with main-stream weirs exhibit smaller extents. No distinct coldspots were identified.

To investigate the environmental characteristics of tributary weirs distribution, we employed an equidistant method to divide elevation and slope into six intervals each and analyzed the distribution patterns of tributary weirs ( $>13.3$  ha) under these intervals. The data in Table 4 indicate that the distribution initially increases but then decreases with increasing elevation. Fifty-five percent of tributary weirs are distributed at 140–180 m, peaking at 160–180 m; those distributed at the peak range account for 32.5%. These findings indicate that weirs tend to be distributed in the middle and upper reaches of tributaries, specifically at the boundary between the basin plain and surrounding mountains. With respect to slope, tributary weirs were distributed mainly on slopes below 5°, with 52.5% concentrated on the 1°–3° gentle slope. The number of weirs decreased significantly as the slope increased.

The clustering of weirs and terrain constraints further led to morphological variations in the canal network system within the IDUs. This is illustrated by the mapping analysis of the morphological typology (Fig. 6). The main-stream IDU is located on flat riverine terraces near Songyin Creek, thus forming an elongated strip. The main canals originate from riverbank intakes and extend along the foothills of mountains and rolling hills, nearly parallel to Songyin Creek. Single-sided water diversion creates branch canals, which then branch into numerous minor canals on both sides, thus maximizing the irrigated area. Tributary IDUs radiate fan-shaped from the hillside toward the river terrace. The main canal extends nearly perpendicular to Songyin Creek from the weir intake. Branch canals diverge from both sides of the main canal, extending toward Songyin Creek.

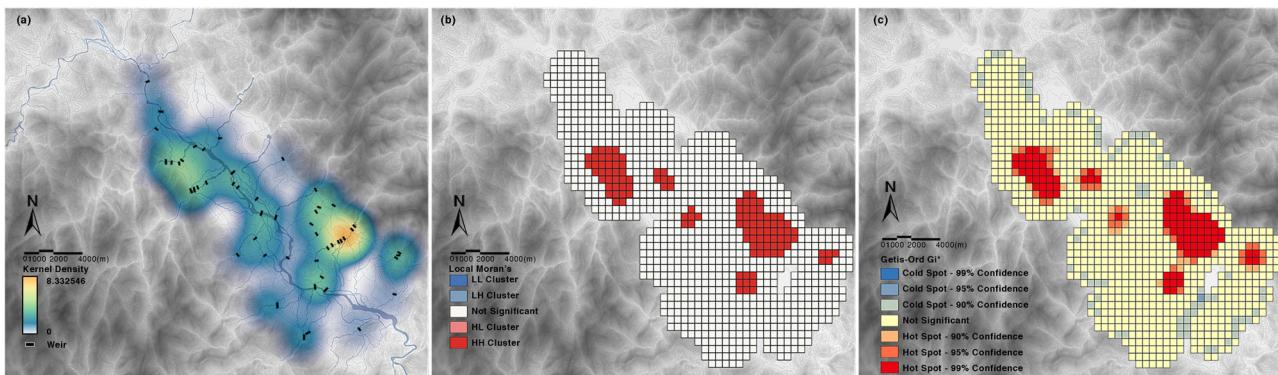


Fig. 5 | Spatial distribution characteristics of weirs. a Kernel density map of weirs. b Local Moran's I map of weirs. c Getis-Ord Gi\* map of weirs.

**Table 4 | Environmental characteristics distribution of tributary weirs (> 13.3 ha) in the Songgu IDCL**

Elevation	Quantities	Per Cent	Slope	Quantities	Per Cent
<120 m	1	2.50%	<1°	3	7.50%
120 ~ 140 m	5	12.50%	1° ~ 3°	21	52.50%
140 ~ 160 m	9	22.50%	3° ~ 5°	7	17.50%
160 ~ 180 m	13	32.50%	5° ~ 7°	4	10.00%
180 ~ 200 m	6	15.00%	7° ~ 9°	2	5.00%
>200 m	6	15.00%	>9°	3	7.50%

The minor canals also diverge from both sides of the branch canals, thereby producing numerous canals whose direction is mainly parallel to the contour lines.

### Agricultural system

Agricultural patterns are significantly influenced by topography and irrigation systems. A mapping analysis of the morphological typology clearly reveals the characteristics of the agricultural textures of the two IDU types<sup>25</sup> (Fig. 6).

(1) Main-Stream IDUs: From river terrace areas to the plains, agricultural textures can be divided into two types: In river terrace areas, embankments are often built to enclose fields or create ponds, thus resulting in the formation of irregular farmland blocks. In the plains, the main and branch canals delineate multiple strip-like cultivation zones. Farmland blocks are uniformly distributed parallel to these canals in regular rectangular plots and range mostly from 0.1 to 0.3 hectares, with aspect ratios between 1:1 and 1:2.

(2) Tributary IDUs: From the foothills to the plains and then to the river terrace areas, three distinct farmland patterns were formed; these patterns exhibit an overall transition from “regular” to “irregular”. In the upper foothill region, characterized by significant elevation differences and limited arable land, farmland blocks are parallel to the terrain and densely and regularly arranged in narrow, elongated strips. Most blocks range from 0.03 to 0.06 ha, with aspect ratios between 1:4 and 1:10. In the middle and lower plain areas, the terrain is flat. Branch and minor canals divide the land into multiple fan-shaped farming zones. Farmland units are arranged perpendicular to the canal network: smaller cultivated blocks at the top of the fan are mostly regular squares. As the cultivated area expands, the farmland gradually takes on irregular polygonal shapes, mostly ranging from 0.1 to 0.3 ha. Near the river terrace, the farmland units are arranged perpendicular to the irrigation channels and are approximately rectangular.

### Settlement system

The formation and evolution of IDCL settlements are shaped by the dynamic interaction between water environments and anthropogenic

activities<sup>57</sup>. On the basis of the spatial relationship between settlements and irrigation systems, settlements can be categorized into three types: weir villages, canal villages, and pond villages. Nineteen weir villages were formed because of the construction and management of nearby weirs. Owing to their proximity to water sources and earlier establishment, these villages exhibit a higher degree of development. Their settlement patterns are fan shaped. Fifty-one canal villages are situated alongside secondary irrigation infrastructures. These settlements evolved because of water accessibility and hydraulic management needs. Initially, the settlements developed linearly along the canals. As the canal network branched into comb-like and fishbone patterns, the settlements transformed into compact, clustered layouts. Ninety-eight pond villages are predominantly situated at the foot of the hill or along the Songyin River. They rely on adjacent ponds for flood regulation and are connected through visible or hidden canal networks (Fig. 7a).

Kernel density analysis was employed to investigate the spatial distribution of 173 settlements within the IDCL (Fig. 7b). The results indicate a density of 0.99 settlements per square kilometer, thereby revealing a significant spatial heterogeneity pattern characterized by a highly dense cluster in the northwest ( $k = 8.33$ ) and a sparse distribution in the northeast and southwest.

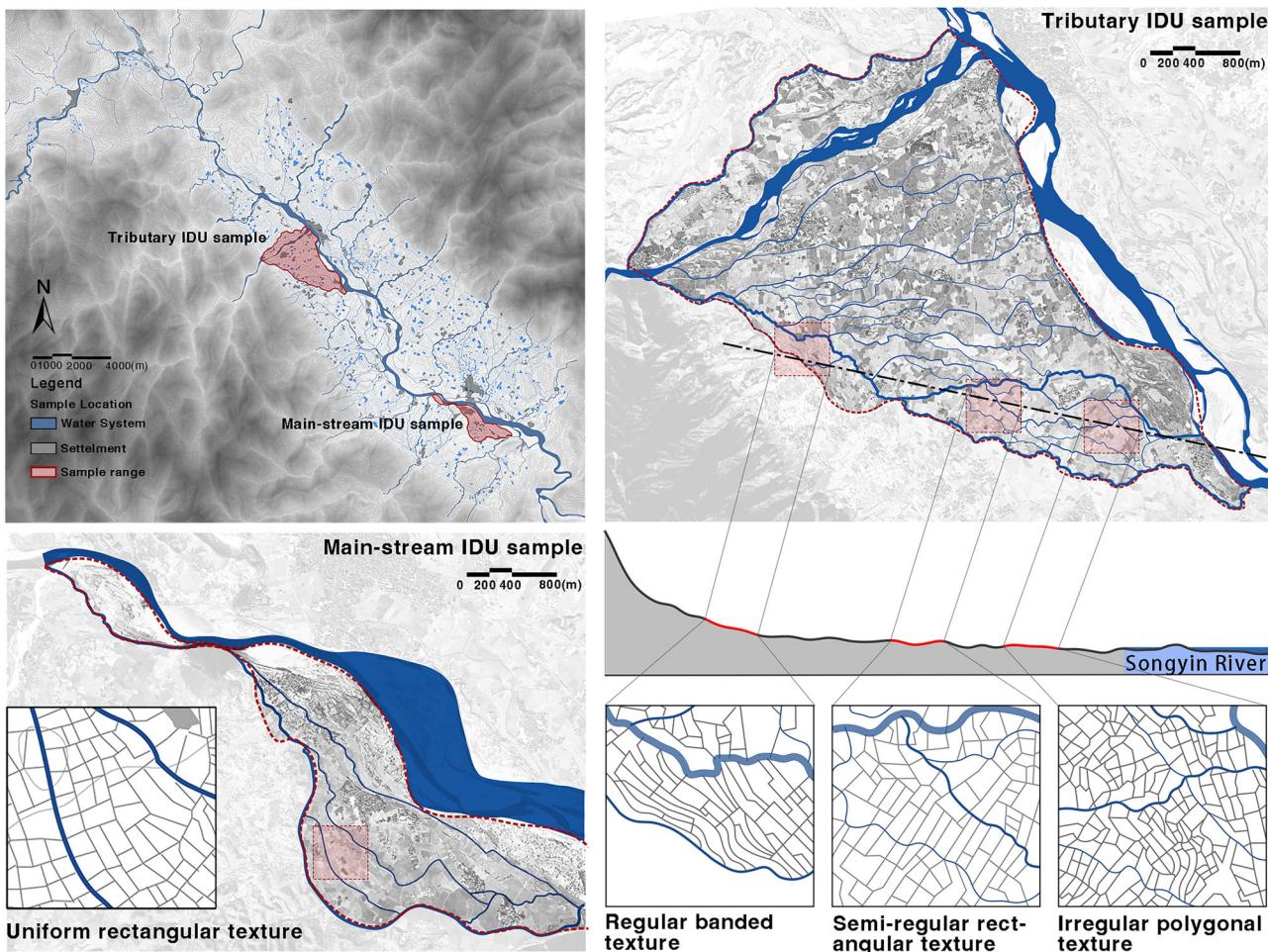
Global spatial autocorrelation analysis yielded a Moran's I value of 0.808460 ( $p = 0.00$ ) and a  $z$  value of 31.603489, thereby indicating significant spatial autocorrelation and clustering among settlements. The  $z$  value for the high-low clustering analysis was 34.093781 ( $p = 0.00$ ), thus further confirming the strong clustering in specific areas.

The local autocorrelation results (Fig. 7c, d) reveal that high-high (HH) clusters appear in F\_IDU and the IDUs of the Xinxing, Jinliang, and Puzhi weirs. No other spatial clustering patterns were identified. Hotspot analysis results reveal that hotspot areas align with HH clusters, with the largest ranges observed in F\_IDU and Xinxing Weir IDUs. Coldspot areas are located at the foothills and cover a relatively small area.

Spatial analysis revealed that the pronounced clustering of settlements is jointly influenced by natural and irrigation patterns. On this basis, mapping analysis was further employed to investigate the morphological characteristics of settlements within the two types of IDUs.

(1) Main-Stream IDUs: Settlements were relatively few but exhibited larger average sizes, approximately 1.5 times those of tributary IDUs. The settlement density is low near upstream water intake points because of flood risks. Settlements predominantly cluster along the middle and lower reaches, thus forming linear belts along main and branch canals. The dominant types are canal and pond villages. Most settlements expand toward farmland, consequently forming a convex structure. This finding indicates that flat terrain imposes fewer spatial constraints on settlement development, with expansion driven primarily by agricultural dependency.

(2) Tributary IDUs: Settlements were relatively numerous. They predominantly followed the pattern of the irrigation network, thereby forming a fan shape. Weir villages, formed at upstream weirs, were often named “Kou” (口), the Chinese character for “mouth”. Settlements in the middle



**Fig. 6 | Sample distribution.** Agricultural textures of the two IDU types.

and lower reaches were located along branch canals, at foothills or near ponds close to rivers. Within the larger IDUs, farmland hinterlands often produced small settlements for the convenience of cultivation.

Overall, the core logic behind settlement location and development remains water resource accessibility and farming convenience.

#### Water-society system

The development of traditional agriculture in the Songgu IDCL critically depends on the effective management of mountainous water resources<sup>8</sup>. Water resources are characterized by shared consumption, high exclusive costs, and competitive benefits, which are among the public resources. Water management faces issues of supply arising from inadequate investment and maintenance and issues of occupation stemming from insufficient water supply<sup>31</sup>. Through an analysis of historical archives, the water-society of the Songgu IDCL can be divided into two main categories: an organizational system addressing supply issues and a water-rights system addressing occupation issues (Table 5).

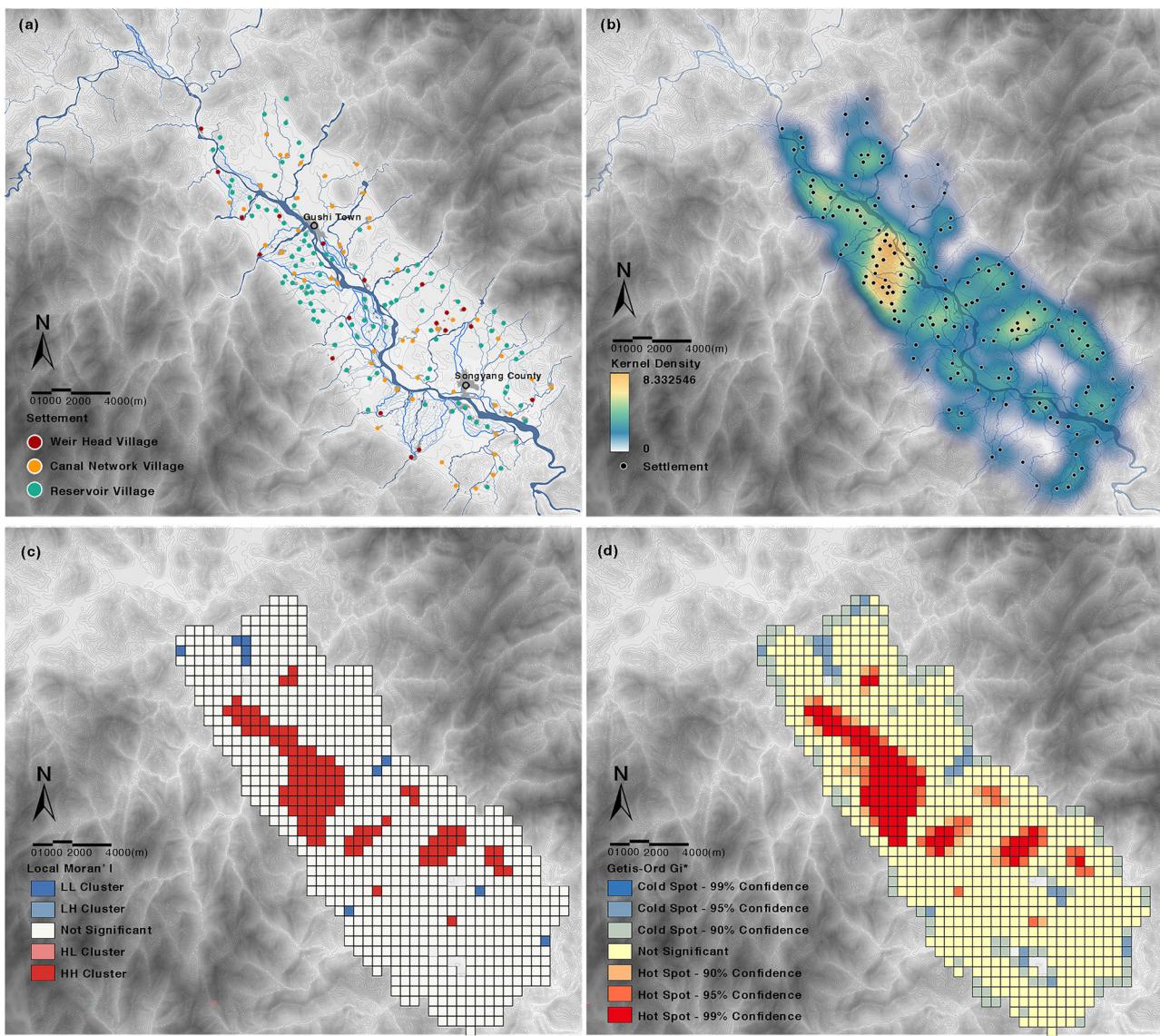
**Organizational system.** The Songgu IDCL implements a three-level administrative management system: the county government, IDUs, and villages. The county government, whose primary functions include irrigation area verification and the legal resolution of water rights conflicts, oversees all IDUs. Within each IDU, the weir council is composed of weir chiefs elected from each village, thus ensuring mutual oversight and balance. This council handles communication between the government and villages, as well as daily management tasks such as repairs, fee collection, and dispute resolution. The funds

for the daily operating expenses of IDUs are primarily raised through water fees or land rents.

Owing to constraints such as administrative boundaries, project scale, and technical complexity, the construction systems differed between the two IDU types. Main-stream IDUs operated under an administrative responsibility system in charge of the county magistrate. Construction funding was typically government funded (e.g., in the case of the Bai Long Weir IDU) or jointly financed by the government and local stakeholders (e.g., in the case of the Qing Long Weir IDU). When irrigation projects were located outside the beneficiary villages, the government coordinated the borrowing of land. The tributary IDUs employed a weir council system led by the weir chief. Construction funding relied primarily on farmer contributions, typically apportioned according to farmland area, thus linking responsibility and water rights.

**Water-rights system.** Water-rights management is authorized by the government, which consistently prioritizes irrigation and bans water trading. In terms of water allocation, the main-stream IDUs is primarily based on farmland area, whereas the tributary IDUs comprehensively considers both weir construction investment and farmland area. The two main types of water distribution methods are as follows: One (e.g., the Jinliang Weir IDU) uses sluice gates of varying sizes to regulate flow to different villages. The other (e.g., the Qinglong Weir IDU, F\_IDU) takes turns opening sluice gates according to each village's allocated irrigation time.

Additionally, the Songgu IDCL has developed bottom-up water-related ritual activities. Villagers erect steles and build temples to



**Fig. 7 | Spatial distribution and characteristics of settlements in the Songgu IDCL. a** Spatial distribution map of settlements. **b** Kernel density map of settlements. **c** Local Moran's I map of settlements. **d** Getis-Ord Gi\* map of settlements.

**Table 5 | Water-society of the Songgu IDCL**

Organizational system	Management system		County government (county magistrate) -IDUs (Weir Council) -Village (weir chiefs)
Water-rights system	Construction system	Governance Financing	<b>Main-stream IDUs:</b> administrative responsibility system; <b>Tributary IDUs:</b> weir council system <b>Main-stream IDUs:</b> government funded or jointly financed by the government and local stakeholders; <b>Tributary IDUs:</b> farmer contributions
	Funds source		Water fees or land rents
	Governing authority		Permission from the Government (notified through official lists, stone tablets)
	Principle		Prioritize irrigation and prohibit water trading
	Water allocation		<b>Main-stream IDUs:</b> farmland area; <b>Tributary IDUs:</b> both weir construction investment and farmland area
Distribution method			Flow regulation method; Time regulation method

commemorate outstanding contributors to water management. For instance, villagers in the Jinliang and Qinglong weir IDUs inscribed steles documenting governors' achievements in water governance, whereas the Bailong Weir IDU constructed a temple honoring donors to water construction projects. These buildings are predominantly situated at weir heads or high ground, thus emphasizing their central role in community spirit and life<sup>46</sup>. Through spontaneous

commemorative activities, these buildings gradually became centers of IDU water conservancy cultural<sup>58</sup>.

#### Spatial and scale coupling relationships

In this study, six main-stream IDUs and five tributary IDUs were selected as samples (Fig. 8) to analyze the interactive relationships among the irrigation infrastructure, agriculture, and settlement layers.

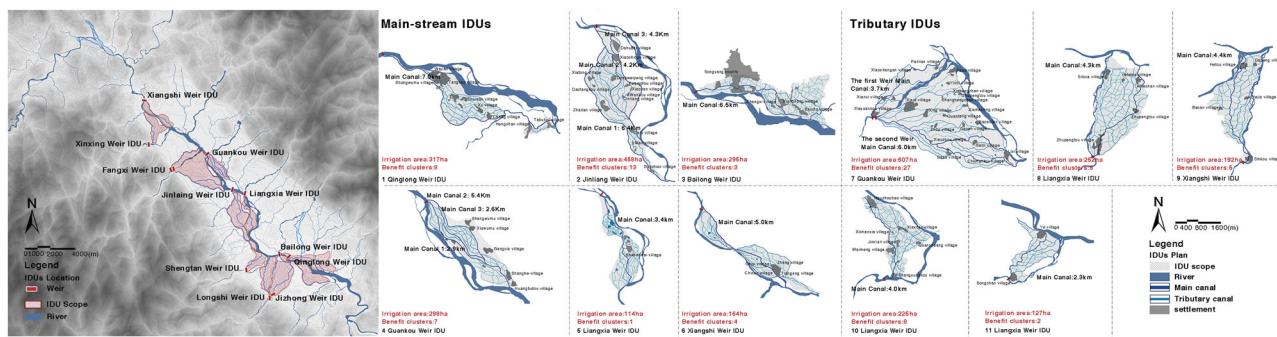


Fig. 8 | Distribution map and structure diagram of selected IDUs.

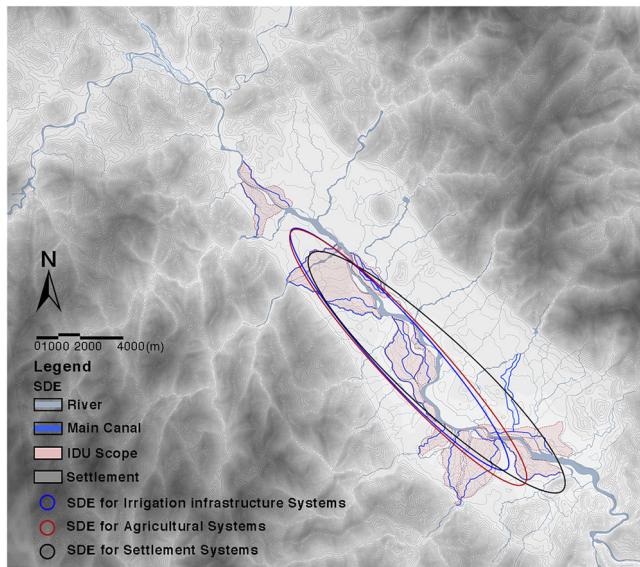


Fig. 9 | SDE. SDE between water conservancy, farmland and settlement of selected IDUs.

The standard deviation ellipse (SDE) analysis results (Fig. 9) indicate that the primary spatial distribution direction of the three-layer system is northwest–southeast; this finding is highly consistent with the Songyin River alignment. The flattening shape of the ellipses indicates that the development of the three systems perpendicular to the Songyin River is constrained by the natural environment. The three ellipses largely overlap, thus demonstrating that the spatial coupling of the three-layer systems is extremely high. The spatial centroid of the settlement system shifts southeastward relative to that of the irrigation and agriculture systems, thus suggesting that settlement development is influenced by not only irrigation and farming but also more factors.

Table 6 provides the relevant statistical data for the selected IDUs. As shown in Table 7, correlation analysis indicated that the main canal length was significantly positively correlated with both farmland area ( $r = 0.972$ ) and settlement population ( $r = 0.860$ ). Farmland area is also significantly positively correlated with settlement population ( $r = 0.896$ ). However, the main canal network density was not significantly correlated with the other variables.

Global Moran's I spatial autocorrelation analysis revealed that spatial autocorrelation was not significant for any variable at the IDU scale ( $p > 0.05$ ). This finding indicates that IDU development is influenced primarily by internal conditions rather than neighboring IDUs. Therefore, the study employs an ordinary least squares (OLS) model to analyze variable relationships.

Two OLS regression models were constructed with farmland systems (Model 1) and settlement systems (Model 2) as the dependent variables. Collinearity diagnostics revealed no multicollinearity interference among the variables (VIF = 1.03). The results (Table 8) indicate that both models passed the significance tests ( $p < 0.001$ ) and exhibited high fit indices ( $R^2_1 = 0.963$ ,  $R^2_2 = 0.925$ ). In both models, main canal length had a significant positive influence ( $\beta_1 = 0.922$ ,  $p_1 < 0.001$ ;  $\beta_2 = 0.938$ ,  $p_2 < 0.001$ ). However, canal network density had no significant influence on farmland area ( $p > 0.05$ ) but did have a significant negative influence on settlement systems ( $\beta = -0.438$ ,  $p < 0.001$ ).

These findings provide compelling evidence for the spatial evolutionary patterns of IDCL irrigation canals extended along rivers, agriculture developed along canals, and settlements clustered around water sources. With respect to the IDU, the main canal was the main driver of agricultural development and settlement. The construction of branch canals and minor canals facilitated field irrigation but spatially constrained settlement expansion.

### The case of Fangxi Weir IDU

The F\_IDU, established during the Song dynasty, is the most developed and largest tributary IDU within the Songgu IDCL and is typical and representative.

**Irrigation infrastructure system.** The F\_IDU primarily draws water from the Shisanduyuan River, incorporating two weirs. Both are situated on the higher-elevation fan necks of alluvial fans. The main canal of the first weir, which is 3.7 km, irrigates farmland north of the Shisanduyuan River. The second weir is located approximately 90 meters downstream from the first. The main canal of this weir, which is 6 km long, irrigates farmland on the southern side (Figs. 10, 11).

Kernel density analysis was employed to reveal the spatial patterns of the main and branch canal networks within the F\_IDU. The data in Fig. 12a indicate that the middle and lower reaches of the second weir's main canal are highly dense clusters ( $K = 0.01$ ). Global spatial autocorrelation analysis of canal network density yielded a Moran's I value of 0.864928 ( $p < 0.001$ ) and a z value of 34.110748, thereby indicating significant spatial clustering in canal network density. Local Moran's I and Getis-Ord Gi\* analyses (Fig. 12b, c) reveal that large-range hotspots appear in the middle and lower reaches of the second weir's main canal. The ranges of high-high clusters are similar to those of hotspots. Moreover, coldspot areas were observed on the Songyin River bank.

Morphologically, the irrigation network of F\_IDU has a fan-shaped pattern. The main canal of the second weir lies along the foothills, with branch canals branching out like tree limbs on both sides. Some branches expand into ponds to regulate floodwater. This irrigation network layout shows typical characteristics of tributary IDUs, thereby providing micro-level case evidence for morphological type research.

The F\_IDU case reveals the spatial heterogeneity of the irrigation network within the IDUs, thereby refining the characterization research of IDCL irrigation systems.

**Table 6 | Descriptive statistics of selected IDUs**

IDU Type	IDU Name	Main Canal Length (km)	Irrigation Area (mu/ha)	Farmland Area (mu/ha)	Settlements Number	Settlements Population	Main Canal Density (m/mu)	Settlements Density
Main-Stream IDUs	1 Gongshi Weir	22.94	2460 (164)	2371 (158)	4	1990	9.68	2.44
	2 Guankou Weir	36.69	4470 (298)	4298 (286)	7	4075	9.00	2.35
	3 Jinliang Weir	66.04	6870 (458)	6495 (433)	13	4555	10.17	2.84
	4 Liangxia Weir	18.91	1710 (114)	1629 (109)	1	1330	11.61	0.88
Tributary IDUs	5 Qinglong Weir	38.74	4760 (317)	4163 (277)	8	4581	9.21	2.52
	6 Bailong Weir	32.8	4425 (295)	2805 (187)	3	4423	11.69	1.02
	7 Xinxing Weir	25.51	3375 (225)	2662 (177)	8	2739	9.58	3.56
	8 Fangxi Weir	117.29	10905 (727)	9118 (607)	27	6942	11.48	4.45
	9 Shentan Weir	21.11	1905 (127)	1762 (117)	2	1455	11.98	1.57
	10 Longshi Weir	32.20	2880 (192)	2710 (181)	5	2021	11.88	2.60
	11 Jizhong Weir	40.78	3780 (252)	3452 (230)	5	3566	11.81	1.98
Weirs	12 Zixi Weir	—	1080 (72)	—	2	—	—	2.50
	13 Puzi Weir	—	1200 (80)	—	1	—	—	1.25

**Table 7 | Correlation analysis of sampled IDUs**

	X1	X2	Y1	Y2
X1	1			
X2	0.179	1		
Y1	0.972**	0.045	1	
Y2	0.860**	-0.269	0.896**	1

\*\*  $p \leq 0.01$ .**Table 8 | OLS regression results**

Dependent variable	Model 1			Model 2		
	$\beta$	t	P	$\beta$	t	p
X1 (Main Canal Length)	0.996	14.378	0.000**	0.938	9.543	0.000**
X2 (Main Canal Density)	-0.134	-1.929	0.090	-0.438	-4.449	0.002**
R <sup>2</sup>	0.963			0.925		
Adjusted R <sup>2</sup>	0.954			0.906		
F	$F (2,8) = 103.576, p = 0.000$			$F (2,8) = 49.414, p = 0.000$		
D-W	1.591			2.095		

\*\*  $p \leq 0.01$ .

**Agricultural system.** F\_IDU irrigates an area of 604 ha, which primarily consists of paddy fields. Rice is the main crop and is supplemented by cash crops such as rapeseed, sugarcane, tobacco, and tea. Mapping analysis was employed to examine the texture characteristics of farmland within the IDU. From the foothills to the Songyin Creek banks (Fig. 13), the farmland texture transitions from “regular” to “irregular”. In the middle reaches, branch canals are predominantly parallel to each other, whereas minor canals intersect perpendicularly, thus delineating semi-regular square farmland blocks of relatively small size. This morphological type represented most of the farmland. In the downstream area, the distance between branch canals increases, and the farmland blocks delineated by minor canals gradually shift to irregular polygons. These findings align with the farmland texture typological classification at the overall scale and further reveal the spatial distribution of different textures within the IDU.

**Settlement system.** F\_IDU is in highly dense settlement clusters of the Songgu IDCL, which contains 23 settlements. Five are in the first weir irrigation area, while 18 are in the second weir irrigation area. Settlements in the first weir area are located near the main canal, and settlements in the second weir area are distributed along branches and minor channels. Settlements in the upper and lower reaches, such as the villages of Xiaoyankou, Xixia, and Lixi, enjoy water resource advantages and are larger than those in the middle reaches (Table 9).

Kernel density analysis indicates (Fig. 14a) that two highly dense areas ( $K = 1.98$ ) are situated in the upstream and downstream reaches of the second weir, which is adjacent to the Songyin Riverbank. Global spatial autocorrelation yielded a Moran’s I index of 0.905880 ( $p < 0.001$ ) and a z value of 36.270185, which indicate a strong spatial clustering of settlements. Local Moran’s I and Getis-Ord Gi\* were used to identify primary hotspots and high-high clusters that coincided with the highly density areas. Cold spots were found in the midstream reaches of the first weir and along the second weir main canal (Fig. 14b, c). Analysis combined with settlement population data indicates that settlements in low-elevation areas with abundant water sources are small but high in density, whereas those along high-elevation main canals are large but low in density.

Mapping further reveals the spatial morphology of different settlement types within the IDU. The weir village (Xiayankou Village) adjoins two

weirs, with its boundaries defined by the main and branch canals of the Shisanduyuan River. The village has a compact, clustered layout. The canal village (Xixia Village) is characterized by internal branches and minor canals, with roads parallel to canals, thus forming water streets. The pond village (Lixi Village) is located in a low-lying area surrounded by numerous ponds. The outside ponds serve irrigation and fisheries, while the ponds within provide domestic water and have developed into communal spaces (Fig. 15).

These findings refine the understanding of the spatial distribution of settlement heterogeneity within the IDU, thereby highlighting the influence of topography and water availability.

**Social-water system.** F\_IDU aligns with the water management model summarized in the overall analysis. Relevant archival materials and historical records provide more detailed evidence of F\_IDU water management. In terms of the organizational system, F\_IDU imple-

mented an approach consisting of a multilevel structure, comanagement and a water responsibility linkage. The multilevel structure refers to an administrative system extending from the county government to the IDU and down to the village level. The Fangxi Weir Announcement from the Daoguang period of the Qing dynasty records that the IDU Weir Board appointed 2 to 6 weir chiefs. Comanagement refers to construction that is legally supervised by government authorities, while specific construction matters are planned and decided upon by weir councils. In addition to the government and weir council, respected elders from each village also participate in management. In terms of water responsibility linkage, IDU project funding and expenses are primarily sourced through farmer fundraising and are apportioned according to farmland area per household.

In the water-rights system, the common principle of “government authorization and agricultural production priority” is followed. However, the water allocation of F\_IDU has undergone repeated interest negotiations and institutional adjustments. F\_IDU employs the irrigation time in turn method to distribute water, with geological alliances as the basic units, which are divided into three major alliances: upstream, midstream, and downstream (Fig. 16). Initially, a 14-day rotational irrigation scheme was adopted, with allocation based on the construction investments of each alliance. However, this scheme caused water shortages for the midstream alliance with larger farmland areas, thereby triggering persistent conflicts. Although an attempt was made in 1688 to switch to allocation according to farmland area, this allocation scheme disrupted existing interests and was forcibly abolished by the state government in 1690. Not until 1824 did F\_IDU establish a comprehensive allocation scheme that combined investments and farmland area. The new 15-day irrigation scheme (specifically, 6 days downstream, 5 days upstream, and 4 days midstream) ultimately resolved water resource conflicts effectively.

Overall, the F\_IDU case reflects the governance interactions between government and village communities, as well as resilient governance centered on water resource allocation, thereby providing detailed evidence for understanding water-society management in the Songgu IDCL.

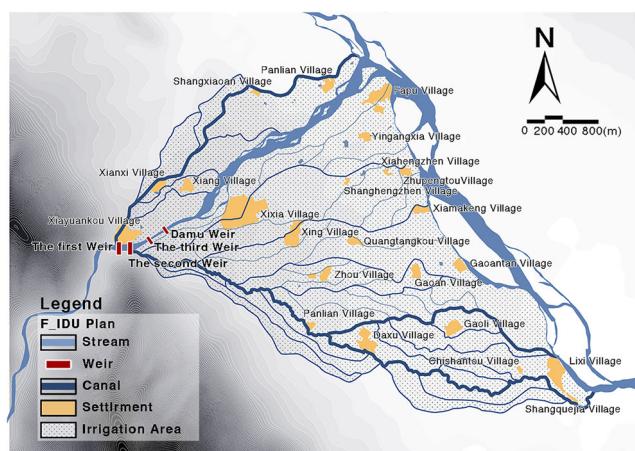


Fig. 10 | F\_IDU Plan. Plan of the F\_IDU.

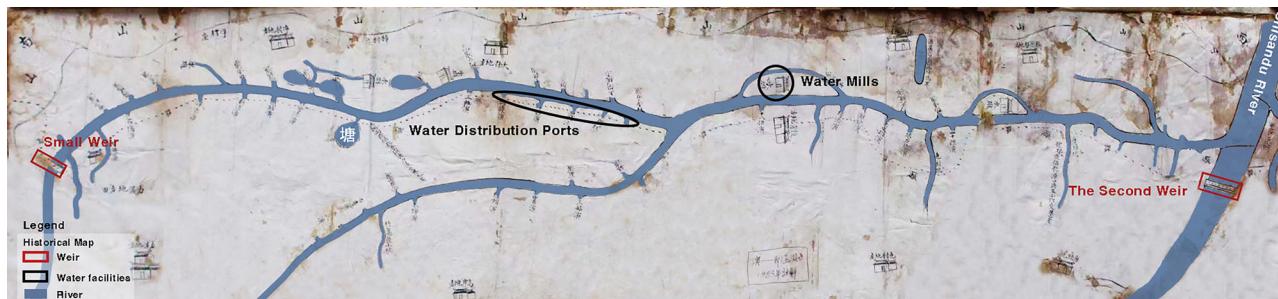


Fig. 11 | Historical Map of the second weir irrigation infrastructure of the F\_IDU during the reign of Hongwu of the Ming period.

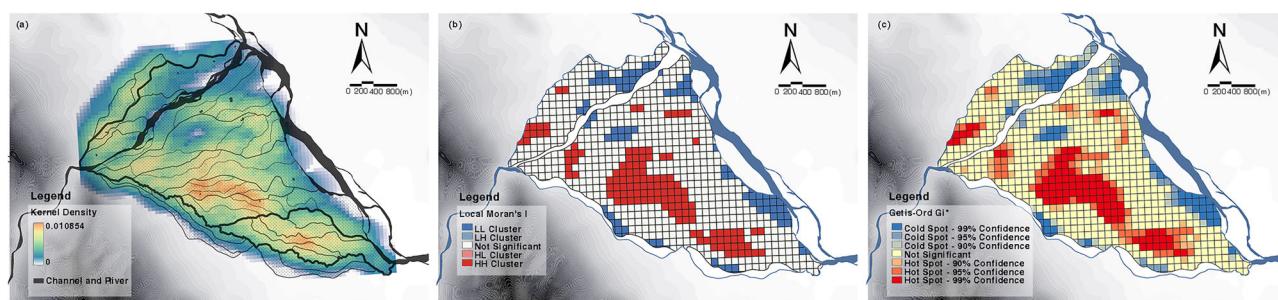


Fig. 12 | Spatial distribution characteristics of canal networks in the F\_IDU. **a** Kernel density map of canal networks. **b** Local Moran's I map of canal networks. **c** Getis-Ord GI\* map of canal networks.

**Standard deviation ellipse analysis.** The primary spatial orientation of the three-layer systems within F\_IDU runs northwest–southeast, thus closely aligning with the direction of the second weir’s main canal (Fig. 17). This finding indicates that the main canal serves as the spatial backbone for IDU development. The three ellipses largely overlap, thus demonstrating a high degree of spatial coupling among the three systems within the IDU. Similar to the overall spatial pattern, the spatial centroid of the settlement system shifts northeastward relative to that of the irrigation and agricultural systems.

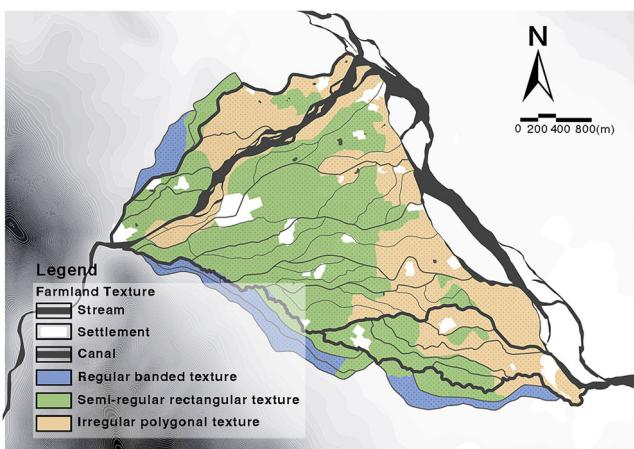


Fig. 13 | Farmland texture. Distribution of farmland texture in the F\_IDU.

## Discussion

This study focuses on the Songgu IDCL, which is divided into five layers—the natural system, the irrigation infrastructure, the agricultural system, the settlement system, and the water–society—according to evolutionary rates and layer relationships. Using a comprehensive approach, including multiscale GIS spatial analysis, morphological typology analysis, and historical document interpretation, we construct a structured and replicable research framework. This multilayer integrative method deepens the interpretation of IDCL regional characteristics; clarifies the interconnections between irrigation heritage, landscape, and lifestyle<sup>59</sup>; and provides a basis for developing effective strategies. The specific research findings are as follows:

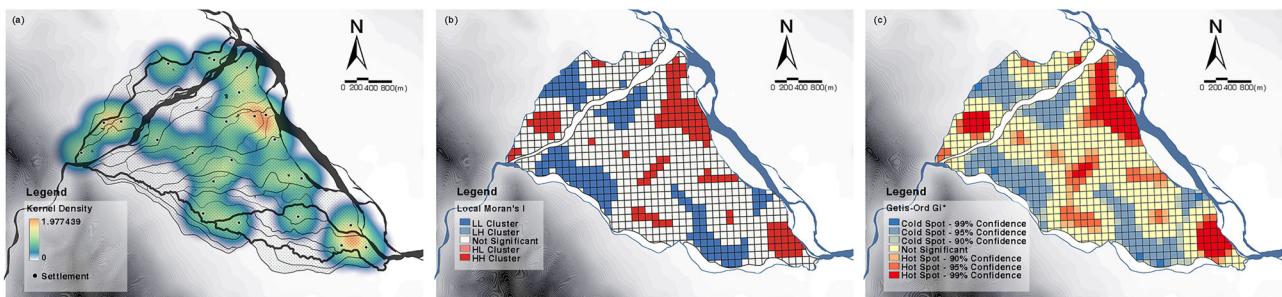
(1) The Songgu IDCL is a surface water irrigation landscape, whose irrigation infrastructure system comprises weirs, main canals, branch canals, ponds, and other elements. At the overall scale, the weirs display a clustered pattern of “two cores and one belt”. Nearly one hundred irrigation IDUs exhibit both commonalities and distinct differences. IDUs can be categorized into two types: those drawn from main channels and those drawn from tributaries, with their channel networks manifesting as strip-shaped and fan-shaped patterns, respectively. Within each IDU, the distribution of channel networks reveals a pronounced spatial clustering pattern.

(2) Agricultural texture exhibits morphological differentiation because of variations in water network distribution. Main-stream IDUs are characterized by regular large fields. In contrast, tributary IDUs display diverse textures influenced by internal topographic variations.

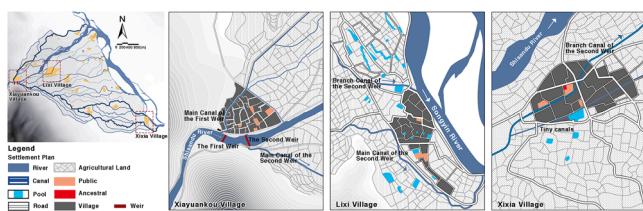
(3) At multiple scales, settlements consistently demonstrate water dependency and spatial clustering characteristics and are typically located around weirs, canal networks, and ponds. Their morphology is influenced by water network patterns and cultivation needs and displays fan-shaped,

Table. 9 | Farmland and population statistics for villages in the F\_IDU

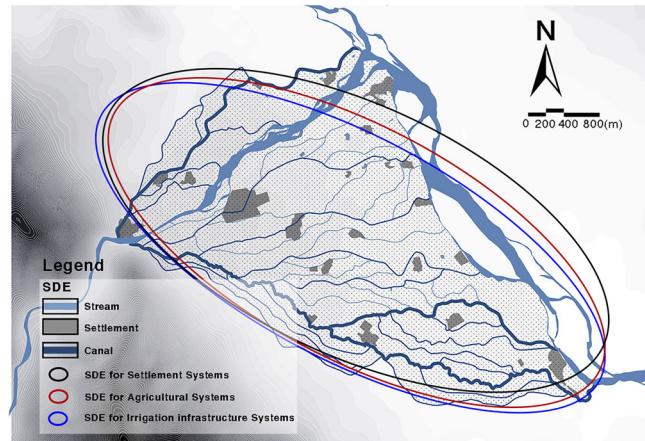
Location	Settlement Name	Settlement Population	Settlement Area/mu	Irrigation Days/Day	Farmland Per Capita
First Weir Area	Xiayankou Village	708	832	—	1.17
	Xianxi Village	201	316		1.57
	Xiangzhai Village	247	287		1.16
	Xiaoshangan Village	391	499		1.28
	Panlian Village	214	329		1.54
Second Weir Area	Upstream				
	Xixia Village	778	937	5	1.20
	Xing Village	316	432		1.36
	Shanghengzhen Village	107	123		1.15
	Xiahengzhen Village	98	121		1.23
	Yingangxia Village	108	149		1.38
	Fapu Village	381	499		1.31
	Midstream				
	Zhupengtou Village	218	222	4	1.02
	Xiamakeng Village	221	311		1.41
	Quantangkou Village	83	132		1.59
	Zhou Village	216	241		1.12
	Shanghouxiao Village	499	621		1.24
	Gaoan Village	368	373		1.03
Downstream					
	Gaoantian Village	186	264	6	1.49
	Gaoli Village	165	263		1.59
	Daxu Village	272	424		1.56
	Chishantou Village	35	—		—
	Lixi Village	1056	1563		1.48
	Shangquejia Village	37	—		—



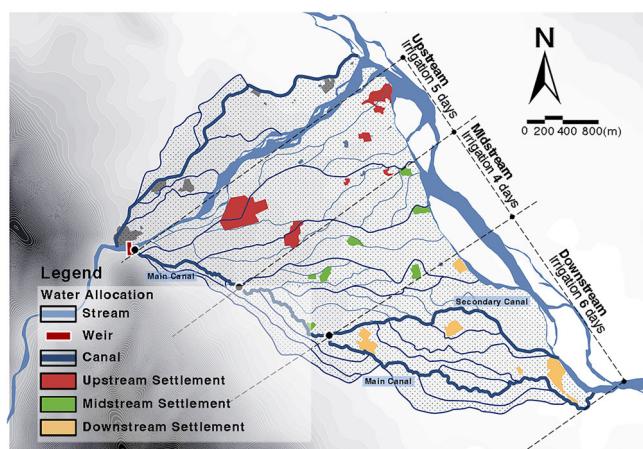
**Fig. 14 | Spatial distribution characteristics of settlements in the F\_IDU.** **a** Kernel density map of settlements. **b** local Moran's I map of settlements. **c** Getis-Ord Gi\* map of settlements.



**Fig. 15 | Settlement plan.** Morphology map of settlements in the F\_IDU.



**Fig. 17 | SDE.** SDE between water, farmland and settlements in the F\_IDU.



**Fig. 16 | Water allocation.** Water alliances and allocation map in the F\_IDU.

clustered and belt forms. Within IDUs, settlement density is negatively correlated with settlement scale; additionally high-density, smaller settlements are mostly located inland of the IDU, far from main canals.

(4) DCL water management operates at the IDU level and encompasses administrative oversight, weir council autonomy, water-sharing alliances, and ritual activities. This system reflects both the state's dominant role in water infrastructure construction and resource allocation<sup>60</sup> while also highlighting collaboration and tensions within community self-governance<sup>61</sup>.

(5) Supportive relationships are among multiple layers of the IDCL. The natural foundation provides possibilities and constraints for irrigation infrastructure projects, whereas the irrigation network determines the agricultural scale and texture. Agriculture and the irrigation infrastructure jointly shape settlement distribution and form. The water society maintains the stability of the IDCL and reshapes the material space<sup>49,62</sup>.

From a global comparative perspective on irrigation heritage (Table 10), the Songgu IDCL can be classified as a medium-scale, multiunit, surface water irrigation system.

In terms of spatial characteristics, the spatial evolution mechanism demonstrated by the Songgu IDCL, where “lower-level material conditions constrain upper-level forms,” is widely prevalent across various IDCLs. However, differences in natural environments and degrees of human intervention produce distinct morphological features among IDCLs<sup>5,63</sup>. This highlights both each IDCL's unique cultural value and the necessity of targeted case studies. Compared with underground irrigation systems, the Songgu IDCL's irrigation infrastructure is characterized by greater visibility and greater morphological diversity. Relative to composite irrigation systems, the Songgu IDCL's irrigation infrastructure results in stronger spatial diversity. Among surface water irrigation systems, the degree of human intervention in the Songgu IDCL is moderate between Dujiangyan and terraced fields, with field and canal patterns combining regularity and flexibility. The F\_IDU case study demonstrates that as water scarcity increases, farmland blocks tend to shrink and become more regular, while settlements remain smaller. This trend is confirmed by a horizontal comparison of the Dujiangyan, the Songgu IDCL, and terraced fields<sup>8</sup>, thus indicating a general coupling relationship between resource constraints and spatial patterns. The diversity of IDUs within the Songgu IDCL reveals spatial commonalities and differences across scales and environments, thereby providing a reference for summarizing general IDCL patterns and understanding human–environment relationships at different scales.

In terms of governance characteristics, existing research indicates that irrigated landscapes are complex sociocultural systems<sup>7,8</sup>. However, significant differences exist in terms of governance patterns across different IDCLs. Dujiangyan represents centralized state management, whereas small- and medium-scale irrigation (whether surface water irrigation or other types) relies primarily on community self-governance. This autonomy uses clan relationships, religion, and rituals to strengthen community identity<sup>43</sup>. The governance framework of the Songgu IDCL integrates these

**Table 10 | Typological characteristics comparison of IDCL**

Irrigation Type	Case	Natural Environment	Irrigated Area	Unit Composition	Degree of Human Intervention	Spatial Characteristics	Governance Mode
Surface water irrigation	Songgu IDCL	River valley	small-to medium-sized	Multiple Parallel Units	Moderate: Channel excavation	Hierarchical linear canal network (main canal–branch canal–minor canal)	Multi-level: government, local, community
	Duijiangyan	Large river basin	Large	Single Unit	Low: Adaptive diversion without weirs	Hierarchical linear canal network relying on natural riverbed	Composite governance: government and local
Groundwater irrigation	Hani terraces	Mountainous and hilly	Small	Multiple Dispersed Units	High: Embankment construction, terracing	Hierarchical terraced canal network	Family or clan-based autonomy
	Karez	Arid region	small-to medium-sized	Multiple Dispersed Units	High: Wells and tunnels	Point-line network of vertical wells and sloping tunnels	Religious or community autonomy
Composite irrigation	Jiangnan Jitang	Coastal plain	small-to medium-sized	Multiple Networked Units	High: Embankments and pond construction	Networked pond–field system	Community self-governance

models and is characterized by co-governance from top to bottom. Government management embodies rigid institutions, whereas autonomous practices embody flexible consultation. This approach helps buffer conflicts among different IDUs and communities while maintaining long-term irrigation order. This approach provides reference experience for the survival and transformation of traditional IDCLs within modern environmental and governance systems.

This study achieves innovation at the theoretical, methodological, and practical levels. Theoretically, this study empirically supplements the “multiumit mesoscale surface water irrigation” type, thereby revealing the unique evolutionary pattern and governance patterns of IDCLs. These findings fill a gap in the literature on IDCL typology. Moreover, by integrating historical geography, spatial statistics, and water–society perspectives, this study reveals multilayered materials and social spatial interactions. It strengthens the theoretical representation of IDCLs as a natural–social composite system and overcomes existing research limitations that focus solely on morphology or institutional aspects. Methodologically, this study constructs and validates a multiscale, multilayer analysis framework. By integrating historical archives, typological mapping, and multivariate spatial statistics, a comprehensive analysis of water conservancy, farmland, settlement, and governance systems can be achieved. The research scale is extended to the regional level, thus revealing the geographical similarities among different IDUs. Their internal variations can also be mapped to other irrigation types, which serve as crucial intermediaries for understanding the universal patterns of IDCLs. In terms of practicality, this study comprehensively delineated the spatial patterns and water–society governance characteristics of the Songgu IDCL. This study emphasizes that the water conservancy system serves as both a core driver and a node of natural and cultural convergence. This provides empirical support for value identification, holistic conservation, and sustainability.

Despite its contributions, this study has several limitations. The sample selection prioritized larger, well-developed IDCs to leverage historical records and represent key IDCL characteristics. This approach may overlook the role of smaller IDCs in local patterns. Furthermore, focusing solely on the Songgu IDCL may limit the generalizability of the findings; future research could enhance empirical validation across regions or different IDCL types. Second, owing to gaps in the historical records, quantitative analysis at the water–society level remains insufficient. Future work could integrate field interviews and oral history materials to more deeply reveal socio spatial relationships. Finally, this study primarily reconstructs and analyzes pre-urbanization IDCL characteristics without systematically examining the modern evolution of IDCLs. Future research should integrate contemporary land use dynamics and social transformations to explore the transition and continuity of traditional IDCLs within modern environmental and governance systems, thereby providing more targeted strategies for cultural landscape conservation and management.

## Data availability

The authors confirm that all findings in this study are supported by data provided within the manuscript.

Received: 21 December 2024; Accepted: 17 October 2025;

Published online: 31 December 2025

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## Acknowledgements

We would like to express our sincere gratitude to the editor and anonymous reviewers for their invaluable comments and constructive suggestions.

## Author contributions

DW, XF and ZC conceived the study. DW analyzed and interpreted the data, drafted the manuscript, edited the final version and prepared partial figures. XF participated in data collection, drafted the manuscript and prepared partial figures. WG and ZC revised it critically for important intellectual content and made substantial contributions to the conception or design of the work. All authors have read and agreed to the published version of the manuscript. WG agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

## Competing interests

The authors declare no competing interests.

## Additional information

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