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Water conservancy projects enhanced local resilience to floods and droughts over the past 300 years at the Erhai Lake basin, Southwest China

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Supplementary material for this article is available [online](#)

Abstract

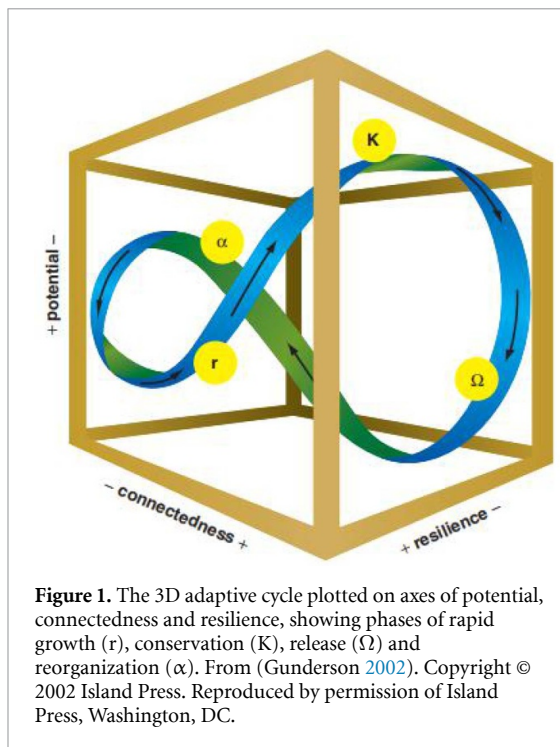
As a typical mountain area at the Yunnan-Guizhou Plateau in Southwest China, the Erhai Lake Basin has uneven precipitation (frequent droughts and floods), affected by the Southwest Monsoon in Asia and significant vertical zonal differences determined by local topography. Though with such harsh physical environment, this area sustained development in ancient times and has been considered a typical resilience case in many studies. With extensive investigation of various historical archives, this paper explores the situation and changes of water management in the Erhai Basin during the past 300 years, and aims to identify local factors in maintaining resilience to water stresses. Findings indicate that various strong and smart social regulations (governance, institutions, plans, management, motivations, orders, donations, dedication, etc.) enabled a wise development of many water conservancy projects that set up an effective irrigation system at the flat basin center. Lots of stream dams, sluice gates and terraced croplands jointly further enabled water storage, drainage and irrigation at the surrounding hillside areas. Additionally, by adopting drought-resistant and cold-resistant crops, agriculture production kept increasing and successfully fed the growing population. The complex but systematically developed river canal system, with its dams, reservoirs, and sluice gates, as well as adaptive cropping strategies, together maintained and enhanced the resilience of local communities to hydrological hazards. Over the 300 years of the study period, the changing water environment and the developing water conservancy projects showed a resilience loop, which offers a simple but valuable perspective on building human-water resilience in face of current and future water crises in this region and beyond.

1. Human–water relationships and the resilience theory

Since ancient times, humans have lived near water since water is the most basic resource for sustaining human life and development. Many civilizations were established and developed along rivers and managed water resources to reduce the impact of floods and droughts (Macklin 2015). On the one hand, human society has never stopped fighting droughts and floods but on the other hand, the development and utilization of water resources over thousands of years have led to spectacular growth in agricultural

production, advanced social adaptation, and control of water hazards and impacts. Meanwhile, the water environment has evolved from a natural system to a coupled system of human and nature (Anderson *et al* 2019).

Research on the human–water relationship essentially promotes sustainable survival and development of human beings in conjunction with a given physical water environment. Recently, the concept of resilience has become a popular theme of the social-ecosystem interface in both academia and practical situations around the world (Folke 2006, Zhou 2017, Liu 2019). The concept of resilience is simply a



measure of the stability of a system that originated from mechanical mechanics and physics and was subsequently introduced into the fields of ecology (Holling 1973) and social-environment relations (Adger 2000, Ge 2010). Holling (1973) suggested the concept of resilience and defined this as an attribute of a system from the perspective of nonlinearity and system theory, referring to ‘the ability of a system to digest interference, reorganize when responding to changes, and basically guarantee the normal function, structure, characteristics and feedback effect of the system’. As reported in recent studies, various measures are used to enhance the resilience of social-ecosystems, including empirical experiences, early warnings, engineering facilities, systematic governance, public participation, emergency responses, etc. (Kwok *et al* 2016, Lewis 2018), thereby increasingly closely linking the concept to practical activities in social-environmental development.

The Adaptive Cycle of Resilience Theory proposed by Gunderson and Holling (Gunderson 2002) refers to the process of a resilient system in the face of continuous and changing disturbances, which provides a foundation to assess the evolution of the social-ecosystem. Gunderson and Holling (Gunderson 2002) described the adaptive cycle as a fundamental unit of dynamic change comprising a forward and backward loop in four phases (figure 1): rapid growth (r), conservation (K), release (Ω) and reorganization (α). This Adaptive Cycle could be developed under human disturbances.

The theoretical models of adaptive cycle strengthen the connection between system resilience, change threshold and system state transition. In the dual loop of adaptive cycle, the dynamic evolution of

r-K reflects the predictable and relatively slow front loop, and the dynamic evolution of Ω - α represents a rapid back loop that has a strong impact on the nature of the next forward loop. In the forward loop, systems self-organize through rapid growth (r) during which free energy is accumulated towards a point of maximum conservation and connectedness (K) and this is epitomized by complex or mature states such as forest ecosystems. In the back loop, perturbations and catastrophes force destabilization and the release (Ω) of potential energy, such as nutrients, soil particles and water, after which the system gradually stabilizes through reorganization (α). Resilience develops between the α and r phases, and declines between the K and Ω phases (figure 1). In resilience theory, the system’s resilience is defined as being able to tolerate disturbance ‘without collapsing into a qualitatively different state controlled by a different set of processes’ (www.resalliance.org/resilience).

As concern regarding disasters in the world increases, more and more studies focus on the resilience of a social system to specific disasters (Tierney 1997, Klein 1998, Mileti 1999). Increasing studies of the human–water relationship during historical periods may reinterpret the adaptive cycle of Resilience Theory. As a large agricultural country, stability of the water supply is an important factor for China and the population. Humans and water are closely linked and research on both the central plain and border mountainous areas of China reflect the profound interactions between humans and water. Even when faced with multiple challenges such as frequent floods and droughts, and rapid population growth, most regions in China have maintained great development throughout history. This is a problem worth pondering that there is bound to be certain water resilience, which enabled the development of ancient Chinese agricultural society.

In this study, we explore water management in the Erhai Lake Basin during the past 300 years and aim to identify local factors involved in maintaining community resilience to risks related to the water supply. After introducing the Erhai Lake Basin and exploring the water problems over the last 300 years, specific water conservancy projects that helped enhance local resilience are investigated. The theoretical resilience loop of the human–water relationship is subsequently discussed and a conclusion proposed.

2. Research area and materials

2.1. Introduction of the Erhai Lake Basin

Erhai Lake (25°36′–25°58′N, 100°05′–100°18′E) is China’s seventh largest lake with a surface area of 250 km². The lake is situated in an intermontane basin between the Tibet–Yunnan fold belt and the Yangtze para-platform. The climate of the Erhai Lake Basin is mainly affected by the southwest summer monsoon with a clear distinction between dry winters and wet

summers. The lake surface is about 1974 m above sea level and has a catchment area of 2500 km². The average annual rainfall is 734 mm, of which 91% falls during May to October, according to meteorological records at Eryuan County from 1957 to 1989 (Zhao 1995). Water sources of Erhai Lake mostly originate from this rainfall.

The Erhai Lake Basin can be divided into five sub-basins (figure 2), with most of the discharge coming from the north supplying more than 59% of the 5.18×10^8 m³ inflow annually. The northern part of the basin is composed of the two sub-basins, Langqiong Basin (浪穹, area A in the left panel of figure 2) and Miju River Basin (弥苴河, area B in the left panel of figure 2). The Miju River Basin was historically the main populated area and major base for crop production, and therefore enjoys a greater focus in this study.

2.2. Materials and methods

This study focuses on the northern catchment area of Erhai Lake (figure 2), especially the Miju River Basin, which is a significant area in terms of historical geography, water environment, anthropological features and social development.

The material resources used in this paper can be divided into the below three categories. The major ones are listed with details in the supplementary (table S1 (available online at stacks.iop.org/ERL/15/125009/mmedia)), which covers various documentary, gazetteer, local chronicles and epigraphic records, and archaeological records of human activities.

- Local records that were produced during the Ming and Qing Dynasties.
- Various archives, including folk documents, inscriptions, folk interviews, etc., especially those in the periods of 1912 to 1949.
- Scientific publications, archaeological discoveries, investigation achievements (such as farmland, soil reports, water investigation reports, etc.) and republished ancient maps. The imperial edicts, memorials and Court Archives of the Qing Dynasty are also effective supplements.

In addition, cartographic technology is taken to reflect the water conservancy projects in history, such as the diagram of water system change in Yong'an Channel basin. We also carried out field investigations in the Erhai Lake Basin in summer 2018 to get first-hand observations on various water conservancy projects, such as the research on Dragon Holes. Several local patriarch and hydrologic experts were interviewed in the field investigation, which included four local officers who are in charge of water conservancy issues in Eryuan and Dali, one local researcher/surveyor on hydrologic facilities, one village chief, and some farmers whose family lived many generations

in the area. Our interview questions focused on the amount and distribution of water conservancy facilities, the construction time, materials, function, utilization, and maintenance of the water conservancy projects.

3. Water hazards and human exploitation in the Erhai Lake Basin

3.1. Water hazards and socio-economical consequences

Floods and droughts are mentioned frequently in historical archives of the Miju River Basin with steep surrounding mountains, due to the influence of the southwest monsoon. Floods and droughts of the northern catchment of Lake Erhai (Simmons 2007, Yang 2007) have been thoroughly documented. In the Miju River Basin, severe floods occurred upstream 41 times and downstream 58 times during the Ming and Qing Dynasties (1382–1912), while droughts were less frequent than floods (Xu et al 2019). We consider a flood to be severe if any losses occurred and were documented due to the flood event, e.g. crop reduction, house damage, injuries or deaths. For example, during the 14th year of Hongzhi in the Ming Dynasty (1501 AD), the basin was flooded because of continuous rainfall and resulted in the flooding of more than 50 Qing (3.3 km²) of farmland and over one hundred people died. Hazardous water events were likely much more numerous than these numbers indicate, as these may not have been documented.

When heavy rains occurred, rising water level break riverbanks and resulted in floods. In 1691, the banks of the Miju River burst and the Chief of the Prefecture, Mr Liang Dalu (梁大路), led local people to plug the leaks. Flood sediments submerged about 79 qing (顷, one qing = 0.067 km²) of paddy fields, causing rice crops to fail. The floodwater runoff also contributed to the deterioration of the water quality (Wu 2012). A huge terrain drop from 2050 to 1987 m asl along the 21 km long river increased potential flood damage to river banks (Yang et al 1996).

Meanwhile, increased cultivation of surface soils on the slopes of the upstream areas (Zhao 1995) resulted in significant sedimentation of the river. Hydrological challenges in the basin area were mainly concentrated at the Miju River (弥苴河) (sub-basin B, figure 1), which is called 'the Small Yellow River' for the high sediment load. Downstream dikes rose above the surrounding farmlands. Torrential floods due to poor drainage and overflowing lakes resulted in significant consequences throughout history, e.g. after continuous rain during the summer and autumn of 1782, water from the Qingbu (青不洞) and Jiulong Gorges (九龙洞) rushed into the Miju River, resulting in flooding of nearby grain fields.

In contrast, weak summer monsoons or rainfall delays could cause droughts, e.g. rice seedlings could not be planted in May 1747. When the monsoon

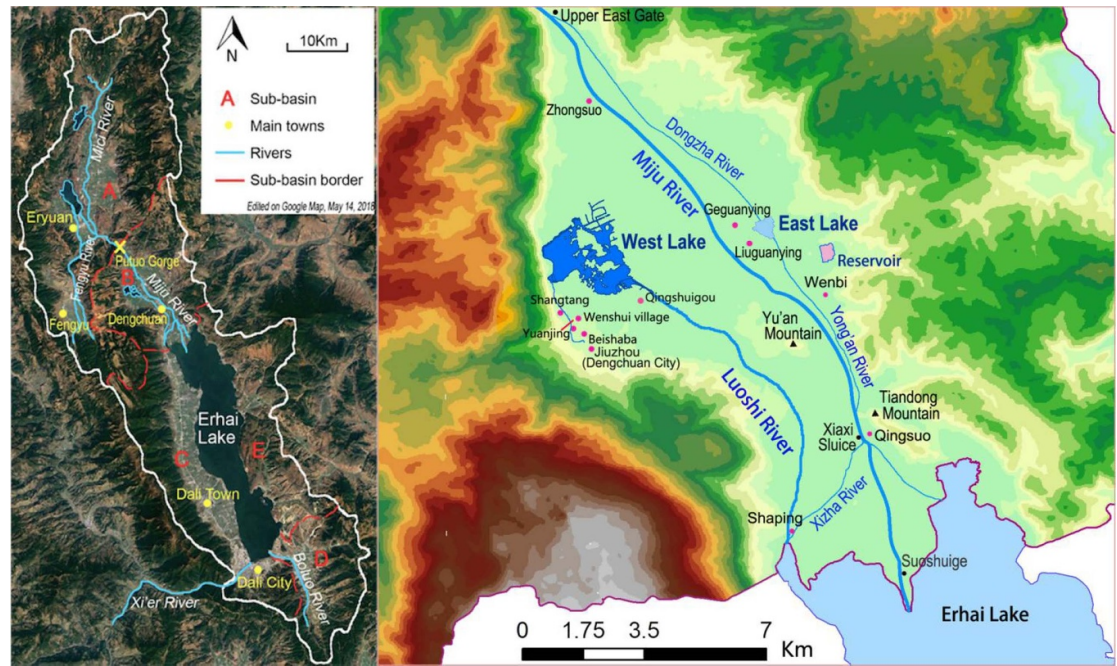


Figure 2. Topography and river system of Erhai Lake Basin (left) with focus on its sub-basin of the Miju River basin (right).

is highly variable, seasonal change may induce both droughts and floods within the same year. In 1859, scarce rainfall in the summer led to drought but excessive rain in the autumn caused the Miju River basin to flood. Weak summer monsoons also led to a scarcity of precipitation and subsequent droughts. Floods and droughts were so frequent that people excavated drainage ditches in the center of the basin and built reservoirs in steep hillside areas.

3.2. Human exploitation and water environment changes

Before the era of the Yuan Dynasty (1271–1368), water hazards were not problematic for the local Bai Ethnic (白族) who mostly occupied high mountainous areas and cultivated rice in terraced fields, while the lower plain areas were flooded swamps and shallow lakes without natural discharge channels (Fang 1987, Fan 1995). When the Yuan and Ming Dynasties were conquered in Yunnan, people from other ethnic groups gradually moved in from Central China and established settlement near the central basin area. The total population of Yunnan in the 26th year of Hongwu in the Ming Dynasty (1393) was about 1.2 million (Cao 2000) and increased to 1.7 million in the Zhengde years (1506–1521). The total population of the Yunnan Province had increased to 7.884 million by the 41st year of Qianlong in the Qing Dynasty (1776), with approximately 746 000 people settled in the Dali region in the Erhai Lake Basin. Despite wars and epidemics, the population of the Dengchuan County has maintained a low growth rate of 1.7% from the 25th year of Qianlong (1760) to the Jiaqing years (1796–1820) (Cao 2000). During this

period, the climate became dry and the shoreline of Lake Erhai gradually retreated (Zhang 1997).

As the population increased after the large migration of 1382, more land near the center of the basin was reclaimed and fertilized, resulting in a high water demand. The Yuan (1271–1368) and Ming Dynasties (1368–1644) farmed in Dengchuan and significantly regulated the river. Agricultural exploitation and construction of dikes were almost synchronized from the beginning of the extensive settlements. During this process, the development of water conservancy and reclamation in the Yunnan-Guizhou Plateau gradually advanced vertically from low-laying basins to mid-alpine mountains (Yang 2007).

4. Water regulation in the flat areas of the central Erhai Lake Basin

4.1. Construction of the Luoshi Channel

As early as the Nanzhao period (738–902), low drainage capacity of the Miju River often resulted in backward flows from the river to the sidelands during summer and autumn, extensively affecting living and farming activities. Large parts of the basin had long been natural swamp fields and existing drainage problems sometimes increased on both sides of the river (West Lake and East Lake, figure 2). High water levels of the Miju River and the two lakes prevented crop cultivation and resulted in the collapsing of houses. Local residents have adopted the proverb, 'A house is built three times in a lifetime', reflecting the negative impacts caused by water in the area. Geographical features such as the steep surrounding mountains, narrow river channels and small water

outlets have contributed to water problems further threatening downstream. Eventually, these led to the construction of the Miju River's bank, and the development of the Luoshi and Yong'an Channels to drain the West and East Lakes respectively.

The West Lake area is low-lying, with poor drainage leading to flooding. As early as the mid-Tang Dynasty (about 763–840 A.D), two local brothers, Luoshi (罗时) and Luofeng (罗凤), excavated drainage canals, digging the canal west of Hill Yu'an (玉案山) according to the terrain and directed the water to Lake Erhai. The water could therefore flow out more easily and the land could be cultivated with a significantly reduced threat of flooding. Local inhabitants named the canal after Luoshi to commemorate the Luo brothers' contribution and the benefits are enjoyed to this day.

4.2. Regulation and maintenance of the Miju River

Construction of the Miju River's bank occurred after military migrants settled in the area, as documented during the Ming Dynasty (1368–1644). Since the Zhengtong years (1436–1450), the army and local inhabitants worked together to build an embankment along the Miju River according to the principle of 'divide the duties according to the amount of grain tax' (分定里界, 按粮编夫). The embankment was completed in 1552, more than 40 miles long with the highest part reaching 20 feet (about 6.7 m) above the ground and enhanced the separation of fields from the swamp. However, due to poor engineering, the sandy embankment often collapsed and the inhabitants had to repair the embankment in the first lunar month every year, with two laborers for each Gong (弓, equal to approximately 1.7 m) of the embankment. Labor assignments for water conservancy works along the Miju River were clearly indicated on an old map (figure 3). This map also showed the levels of flood protection assignment of each section on the bank, including danger (险), thin (单), critical (要), right here (是) that were related to the condition of the river bank and the degree of hazard of the flood. River management work during the 21st year of Jiaqing (1816) was so successful that river problems abated for over 30 years.

4.3. The Dragon Hole system for water discharge and diversion

Since the river was fed by rain, rising water levels resulted in the river embankment bearing enormous pressure and endangering farmland on both sides. In addition to the easy breaching of sand dikes, other factors related to dike failure included elevation of the river bed due to siltation and peak flood height that ultimately depended on the carrying capacity of river dikes. After water flowed from Putuo Gorge, water of

the Miju River surged and broke the riverbank, causing a great deal of damage to the environment. The simplest way to reduce the pressure on the dikes was to open the sluices to discharge floods.

During the Wanli years (1573–1620), the Upper East (上东闸) and West (上西闸) Gates were first opened and water was diverted to the Miju River from early on upstream so as to reduce the midstream water level. The channel was subsequently named the Dongzha River (东闸河) and drained into the East Lake. Although these sluices were abandoned during the Xianfeng years (1851–1861) of the Qing Dynasty, opening the sluices along the Miju River became important for bank protection and flood control.

Spillways on the embankment of the Miju River were locally known as 'dragon holes' (龙洞, in figures 3 and 4). These were water discharge tunnels controlled by sluice gates that appeared as early as the mid-Ming Dynasty. A dragon hole was a type of box culvert with a large tunnel at the riverside, a sluice gate and a few small tunnels on the outer side of the river (figure 4). The sluice gates could be opened and closed at any time to adjust the river water level and irrigate surrounding farmlands. The first dragon hole was built along the Miju River in the 31st year of Jiajing (1552), when governor Bao (鲍, 巡抚) appointed two officers to construct dragon holes after a burst embankment caused a flooding event.

Dragon holes were indispensable elements of the Miju River water conservation system for a long period of time. A dragon hole was designed to release floodwaters during the rainy season and could also be opened to release water and irrigate farmland during the dry season. After the embankments of the Luoshi (罗时江) and Yong'an Channels (永安江) were constructed, the swampland was dried and converted to farmland and this affected the cultivation of grain during dry times. Therefore, there was a need to open sluice gates of the dragon holes and discharge water to irrigate the farmland on both sides of the Miju River, especially during the dry season. Crook and Elvin (2013) also emphasized the significance of dragon holes, pointing out that gravitational flow controlled by the sluice gates was all that was needed to irrigate the fields of further surrounding areas.

Dragon holes had a positive effect on flood discharge and irrigation with a flow rate reaching a total of $10.6 \text{ m}^3 \text{ s}^{-1}$ (table S2). During the Kangxi years (1662–1722), Xu Xiran (徐熙然) opened the sluice of the Suopi Bridge (梭疋桥) to drain the tail of the Dongchuan River into the Xizha River, purely to regulate the water source for farmlands in the lower reaches of the Miju River. During the period of the Republic of China (1912–1948), the sluice was blocked and prevented from discharging, and this triggered a dispute over the sluice of the

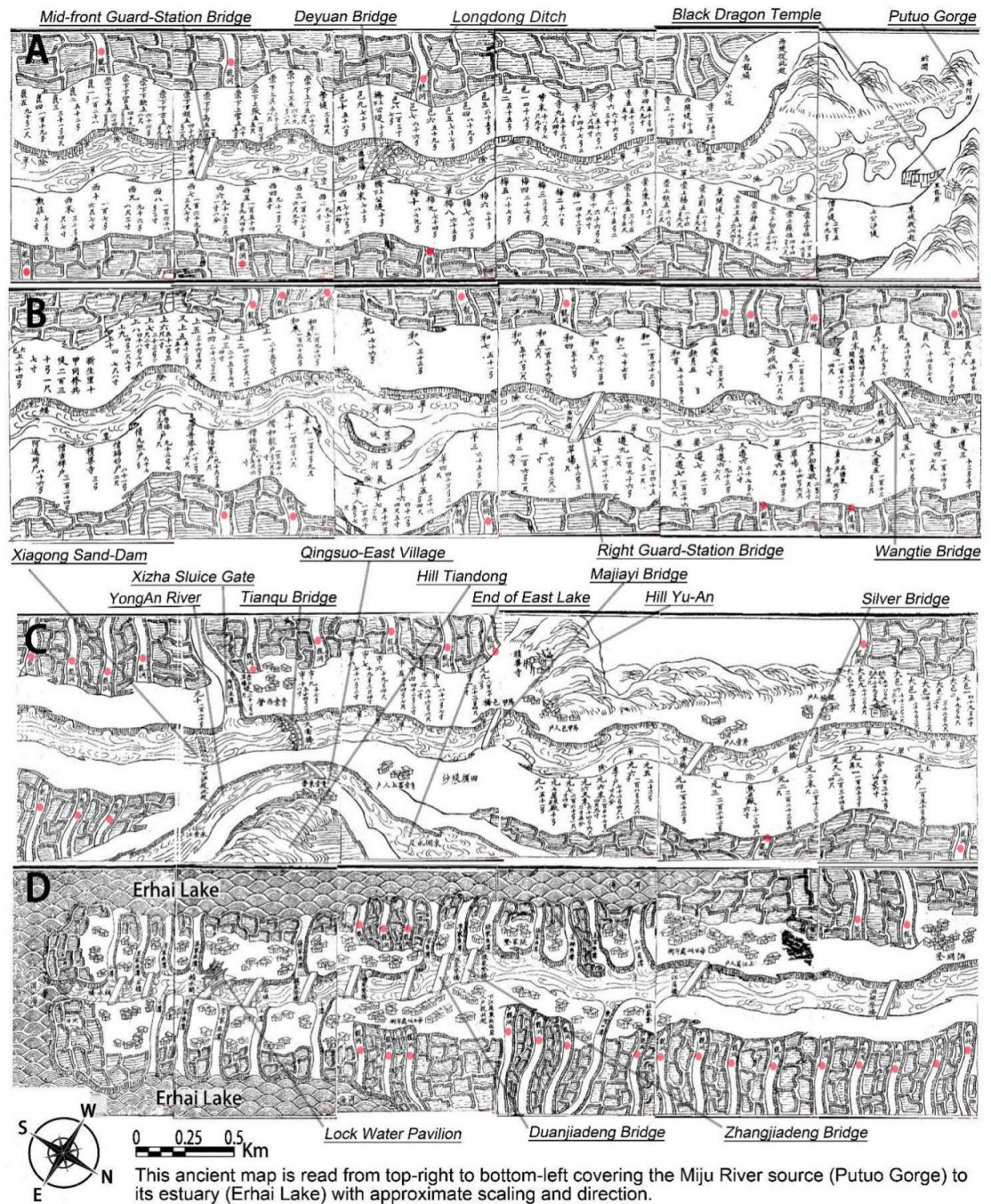


Figure 3. ‘Maps for Hydrologic Works’ from the Local Gazetteer of Dengchuan printed in 1854–1855 (Hou 1854). It shows the assignment of labors along the riverbank as well as the locations of Dragon Holes and Fishing Ditches. Red dots indicate the locations of Dragon Holes.

Suopi Bridge⁵. The opening of dragon holes helped relieve flood risks during rainy seasons and alleviated drought conditions during dry seasons but these also increased drainage pressure in the East Lake area. But the dragon holes can be weak points of burst without good management, especially in heavy rainy days. To safeguard embankments and Dragon Holes, households in villages along the river were responsible for

maintaining the dragon holes. Dragon holes continue to play a significant current role and more information related to identifiable dragon holes is listed in table S2.

4.4. Construction of the Xizha canal at the lower basin

Historically, East Lake was large and shallow, up to a maximum of 14 km² (figure 5). The drainage river had been called the Mandi River (漫地江, meaning overflow), implying that the overflow problem was serious. During the middle-late Ming Dynasty

⁵ Dali State Archives: No. 130-3-3, Notice and announcement on order farmers live by both sides of Yong'an and Luoshi Rivers to control dragon holes as soon as possible for safety.

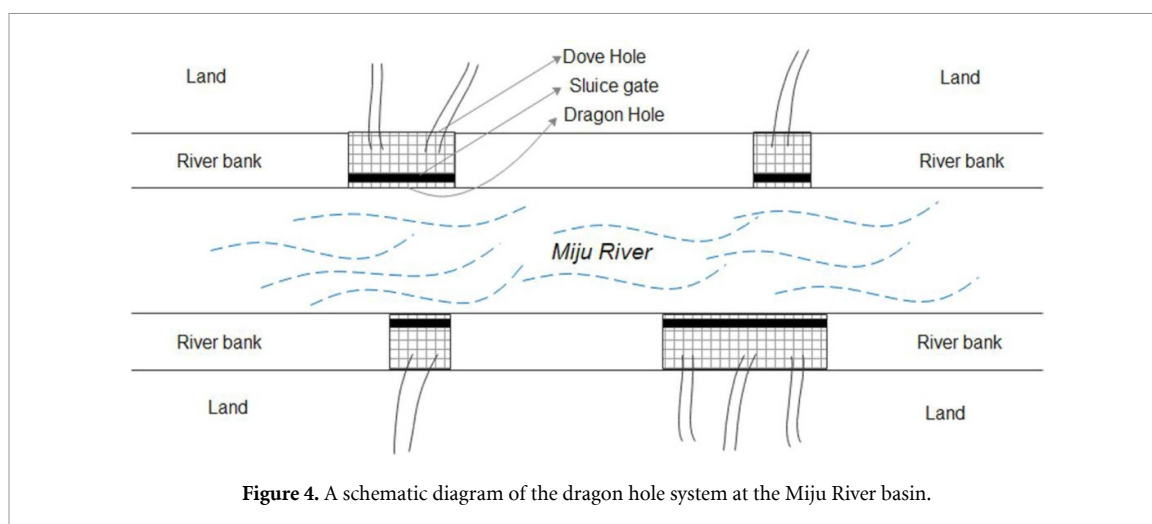


Figure 4. A schematic diagram of the dragon hole system at the Miju River basin.

(about 1436–1661), the deposition and river bed became higher, preventing the lake water from draining out, thereby changing the drainage situation of East Lake. By the middle and late Qing Dynasty (1736–1911), the backflow problem had escalated, causing the flooding of farmland and homes in the East Lake Basin.

In the early years of Kangxi (1661–1722), local residents and gentry opened the Xiaxi Sluice (下西闸) and Xizha Canal (西闸河, figure 2) on the west bank at the Qingsuo Bridge (青索桥). This became an important flood diversion canal and the main irrigation canal at the river estuary, that benefitted more than 2 km² of land along both sides of the river and improved fishing. Further detail regarding the Xizha Canal are available in supplementary section 3.

4.5. The ‘two rivers with three banks’ strategy and Yong’an Channel

Local people realized that the effects of flood discharge from the Xizha River remained limited. Therefore, the East Sluice (东闸) was opened in 1740 and a ditch was excavated to divide the backflow. From February 1781 to the summer of 1783, local people enacted the renowned policy of ‘two rivers with three banks’ (两河三埂策). The inhabitants purchased the land at Qingsuo on the East Bank to open a sub-river and shared the middle bank to drain the water from the East Lake to Lake Erhai separately. This new channel was called the Yong’an Channel (永安江) that ensured safety forever and improved the east basin drainage situation greatly.

The Yong’an and Luoshi Channels became drainage canals of the Miju River Basin. Prior to this, the framework of river systems in the basin was that of ‘one river for irrigation and two rivers for drainage.’ However, this change in the water environment caused negative impacts. The old East Sluice (旧东闸) discharged the river backflow, providing water for irrigation and fishing. Closure of the sluice

resulted in a water shortage that caused drought and prevented cultivation in the East Basin due to a lack of supply from the Miju River. Local inhabitants compromised by building the Down East Sluice (下东闸) that was closed during the rainy season to avoid backflow and opened when water was needed.

4.6. Retaining dams and sluices at the Estuarine section

The Yong’an and Luoshi Rivers were so straight that the water of Lake Erhai flowed back and difficulties occurred with irrigation of farmland in the upper reaches. Sluices were therefore established at the estuarine section of the Yong’an and Luoshi Channels to raise the water level during the dry season and to block the backflow of lake water when Lake Erhai had a high water level. Sediment in the river led to the rapid growth of the estuary delta and created a large area of farmland, named ‘deng’ (登) meaning relatively higher topography, and this was conducive to the development of silt farming for local inhabitants. To obtain sufficient water for irrigation, temporal retaining dams were built to block water at the estuarine section of the Luoshi Channel.

However, installing the retaining dam at the estuarine section hindered drainage of the upper and middle reaches of the river and the conflict between the upstream and downstream sluices has continued. To mediate the conflicts between upstream and downstream sluices, timing of the opening or closing of the retaining dam was controlled by the Water Management Committee, regardless of the incidence of flood or drought. The riverbed of the Miju River at the estuarine section was too narrow for effective drainage, therefore more than a dozen ditches were excavated in the delta to relieve the pressure of flood discharge and used to irrigate farmland in the delta. These ditches were convenient for local fishing and were therefore also called ‘fishing ditches’ (渔沟) (table S3).



Figure 5. The East Lake and its location in the Miju River system, with names of major places.

(Note: The historical area of East Lake in its largest is outlined by the dotted line, and the recent lake area in 1950 is outlined by the solid line, while the lake was disappeared since 1956).

5. Water conservancy in the surrounding mountainous areas

5.1. Water storage projects

At times when rainfall is low or the rainy season late, mountain stream water is often insufficient for irrigation. In areas where natural water is present in the semi-mountainous areas at the feet of the East and West Mountains, crops cannot be planted during the dry season. There are many water regulations in villages in areas of water shortage, with various stone grooves for water diversion and disputes over water could occur frequently.

During the late years of Jiajing in the Qing Dynasty (1522–1566), Yang Nanjin (杨南金), the chief magistrate of Dengchuan County, built a pond using spring water from the North Fengzangjian Mountain (凤藏涧北山). This was locally known as ‘Yushitang’ (御史塘) but is currently called the Yanshi Reservoir. This reservoir irrigated more than 100 mu (亩, about 0.067 km²) of farmlands in the surrounding mountainous and foothill areas. Indeed, many more reservoirs were built during the Ming and Qing Dynasties,

including the Wenbi Pond (文笔塘) and Ganhaizi (干海子) in the Miju River Basin, with a total water storage capacity of about 200 000 m³. After the founding of the People’s Republic of China (1949), two medium-sized reservoirs and more than ten small reservoirs were built from mountain slopes to the central basin areas. Some of the main reservoirs are listed in table S4. Provision of water from these reservoirs has greatly improved the irrigation of farmlands in mountainous areas.

Water use in high-altitude mountainous areas was challenging. Most irrigation canals were jointly constructed and managed by several villages. There were few channels beyond the jurisdiction of the village or mountain streams and ditches were controlled by individual groups. Futian Village struggled with water shortages for a long time. A small-scale water conservancy project, the Fish-Scale Pit (鱼鳞坑), played an important role in drought relief. Approximately 120 small dams and ponds remained functional until the 1990s, with most located in the northeastern part of the Miju River Basin. The total effective reservoir capacity was 36.17 million m³ (table 1) and

Table 1. A statistic of the functional small ponds and dams in 2019. Reproduced with permission from Zhao (1995).

Region	Amount	Total water storage (10 000 m ³)	Irrigation area (km ²)
Jiangwei 江尾乡	8	5.6–6.0	–0.107–0.167
Dengchuan 邓川乡	4	2.0–2.5	0.1–0.16
Yousuo 右所乡	35	39.0–42.0	0.453–0.733
Total	47	46.6–50.5	0.6–1.06

agricultural cultivation was not delayed despite a lack of rain for seven months.

Material resource: Water Conservancy Records of Eryuan County, p 134.

Local inhabitants used various reservoirs and ponds to store natural water (e.g. rain and spring water) before the Dachun period (May to September) for use in future rice plantings. This system was known as ‘borrowing land to store water’ (借田蓄水) and provided 60–80 million m³ water every year for irrigation even during times of drought.

5.2. Construction of banks against mountain torrents

Reclamation of mountainous areas resulted in soil erosion and consequently increased river sedimentation. The purpose of building embankments in mountainous areas was therefore to reduce the velocity of mountain surface flows and retain sediments. Open sluice gates were built at the same time as the embankment system. Gates could be opened to release the water flow and clear deposited sediment and this was considered effective and praised as ‘a good water control strategy’ (Hou 1854).

However, serious floods were often caused by human activity. Local forces of the minority nationality were particularly strong, therefore the construction of dikes met with a great deal of resistance. Many powerful people resisted official orders or obeyed perfunctorily, therefore some levees could not be built or collapsed shortly after construction and mountain torrents could not be managed for hundreds of years. High-ranking officer Jiang Long inspected Dengchuan and assign officers along with local gentries to construct embankments against mountain torrents in 1524. The Miaohou, Yuanjing and Dashuichang Banks were constructed within five months and trees were planted on the bank reinforcement. Many embankments were constructed in foothills at later stages and some remain functioning to the present day, e.g. the Yuanjing Bank at the hillside between Yuanjing (圆井村) and Wenshui Villages (温水村) (figures 2 and 6). Some of the banks are listed in table S5.

5.3. Introduction of drought-resistant and cold-resistant crops

As the population increased, increasing food demands presented challenges for farming. Agricultural cultivations were limited due to steep mountainous fields, variable climate, unreliable water irrigation

and frequent hazards. Fortunately, the introduction of high-yield dryland crops such as corn and potatoes provided new opportunities for Yunnan Plateau during the Ming and Qing Dynasties. Corn was more suitable for the cool, dry mountainous climate than rice, wheat and other traditional food crops. According to the general annals of Yunnan Province (新纂云南通志·物产志) (1949), corn could grow on barren mountains in the middle of Yunnan that were not suitable for wheat and could replace the main traditional grains, i.e. rice and wheat for livestock and wine production. The stem, leaf and bract skin of the corn could be fully utilized as firewood without any waste, therefore corn became the most important economic crop of the planting scheme in Yunnan.

Local farmers found that potatoes could be irrigated approximately once a month when less water was available and that these also grew well at lower temperatures. Potatoes were often planted during the dry period from Xiaoxue (小雪, November 22–23) to Dongzhi (冬至, December 21–23). Potatoes provided dietary diversity for local inhabitants and became popular in the mountainous areas. According to Chen Hongmou (陈宏谋《种植杂粮广树植状》), inhabitants of Yunnan also consume radishes, yushu (蕨薯) and other crops. These can be planted in different types of soil and climatic conditions, and can tolerate dry conditions and soils with poor nutrient status.

During the Ming and Qing Dynasties, especially after the middle of the Qing Dynasty, the general cultivation of high-yield crops in dry land significantly alleviated land productivity pressure in the plateau and mountainous areas. The drought-resistance and cold tolerance of the high-yield crops enabled local agricultural production to overcome the limitations of poor water conservancy and decentralized farmlands in the mountainous areas, and playing an engineering effect by means of agronomy.

6. Resilience loop in the Erhai Lake Basin

6.1. Various measures for enhancing local resilience

Dengchuan inhabitants implemented various measures to cope with the harsh natural conditions, including constructing banks to restrain water flow, dredging the riverbed to promote the smooth water-flow, building reservoirs to store water and setting sluices to control the water. During the Yuan Dynasty (1271–1368), embankment constructions were



Figure 6. Yuanjing bank (photo by Anning Xu, July 10th, 2018).

mostly managed by local governments. The water control system managed jointly by the military, migrants and aboriginal people began during the early Ming Dynasty. The basic principle of the river management system from the Yuan Dynasty and early Ming Dynasty was the ‘east military and west civilian’ (东军西民) system, in which the military was responsible for the construction of the East bank of the Miju River and civilians for the West bank. Until the Mid Qing Dynasty, as reform of basic administrative regions occurred and the military registered residence to the Xiangli (乡里), embankment construction work was delegated to all households. Each family was responsible for repairing a section of the bank and dredging mud in the river.

To ensure successful river management, a system of supervision and punishment was established. A supervisor was dedicated to promote and supervise high quality the work of each family. Other assistants such as messengers and clerks were also engaged in each section of the river. If any worker were slack in their job, they would be pressed to accomplish the job quickly. If the responsible person refused to work according to the contract, a forfeit needed to be paid. Costs for the river engineering project included the labor cost for the construction and maintenance of the river embankment and material cost for the construction and repair of the embankment. Funds for maintaining the river engineering project were acquired from donations from government officials and gentry, assessments specific for river engineer project and land rent.

Although the revenue received from the beginning of the Ming Dynasty was limited and difficult to collect, there was enough to meet the needs of the development of the river engineering project. As

the water environment changed, especially during the mid-Qing Dynasty, a special water conservancy fund was established to support public property. A special land area was established and the income from the land rent was used to fund the construction of the water conservancy that is known as ‘Hegong field’ (河工田).

6.2. Development of the human–water relationship

Various mitigating measures helped communities cope with water risks to a certain extent. As new water problems arose, new measures and solutions were developed and applied to improve water management. The process developed over hundreds of years and formed a positive human–water relationship that enabled the local population to transition into more productive and efficient modern times.

The gradual development of the basin area was accompanied by constant maintenance of the waterways. Evolution of the Miju River system was a process in which the main channel was gradually restored, tributaries were continuously dredged, and the end canals were excavated and diverted. The process of marshes dried-up gradually, paddy field continuous formed and the evolution of the river system, which could be described as rapid growth (r) as defined by Holling (2001).

The water environment keep a relatively stable state (K) after the restoration of the riverbank. But, new problems arose and formed the release stage (Ω), in which the water environment tend to deteriorate. For one thing, the weak part of the river embankment was in danger of collapsing during the peak flood period. For another, the drainage channels, known as Luoshi and Yong’an Rivers, were too straight to hold water, leading to excessive drainage,

causing or exacerbating the drought problem during the planting season of the central basin area. Therefore, dragon holes were opened to play a dual role in releasing floodwaters during peak flood periods and irrigating farmland during drought periods. The water environment looped into the reorganization stage (α).

For the subsequent loop, the system could be described as rapid growth (r), for the excavation of canals increased the density of the rivers in the basin, resulting in the Miju River Basin developing from a shallow marshland into residential areas and farmlands. In an ideal situation, in which dragon holes were well maintained and other factors were eliminated, the water environment could keep at the conservation (K) stage, floods and droughts could be managed as well. Results indicated that the resilience loop of water environment could be maintained at some level or even diverted towards better situation under human disruption before finally collapsing (Ω).

In fact, the four processes overlapped and were partially synchronized. Water consumption increased significantly due to immigration, mainly during the Qing Dynasty (1636–1912). Driven by the increased pressure on land productivity, more agricultural fields were gradually reclaimed up to higher altitude areas. At the meanwhile, reservoirs and small ponds were constructed on the mountain or hillside to store water. Thereafter the human–water relationship can be described as a new rapid growth (r) or the reorganization (α) stage.

This loop system occasionally had stage jumps. As the higher altitude areas in steep hillsides were reclaimed and get into the rapid growth (r) stage, the local inhabitants developed a method of water storage known as ‘borrowing land to store water’ and the resilience system of human–water relationship jump into the reorganization (α) stage. The new method could provide irrigation water and moderate the ground temperature during cold months.

Some water resilience loop characteristics in the Miju River Basin generally fit with parts of the adaptive cycle in the resilience theory described by Holling (2001). The resilience loop could be contained under the intervention of human water conservancy construction activities. After a large immigration, the water environment was subject to a period of rapid development, including dike construction that could be described as a rapid growth (r) stage. Meanwhile, the development of the region caused a sharp deterioration in the condition of the environment and associated water disasters and this was considered a ‘serious ecological crisis in the Ming and Qing Dynasties’ (Zhou 2015). At that time the water environment faced the threat of entering into the release (Ω) period. In some cases, these projects deteriorated and coping measures proved to be ineffective, leading to a new loop of the deterioration of the human–water

system. Local inhabitants dealt with difficulties at different historical stages and mainly maintained the human–water relationship in the conservation (K) state.

6.3. Updated resilience loop of human–water relationship

According to resilience theory (Holling 2001), the adaptive cycle as a fundamental unit of a dynamic process comprises a forward and backward loop with four phases but complete cycles in the sub-basin cases of the human–water relationship in the Miju River Basin cannot be identified. A lack of consideration of social processes and man-made adjustments may lead to deviations. The evolution process of the human–water system did not necessarily follow this cycle of four phases, and if so, these could also likely occur at the same time rather than being distinct or defined separately. This may be the distinction between a real system and a theoretical ideal.

The water situation in the Miju River Basin could be maintained by human influences to prevent the human–water relationship from collapsing. For example, during wartime, water conservancy construction activities usually ceased. According to a local archive⁶, in the late Qing Dynasty from the Xianfeng to Tongzhi years (1851–1875), a large-scale Muslim Revolution led by Du Wenxiu (杜文秀) broke out in western Yunnan, centered in the Erhai Lake Basin. The war caused a large-scale plague that significantly decreased the population and this negatively impact the cultivation of croplands and the water conservancy development. The resilience of the human–water relationship was disturbed or even started collapsing and this could be described as release (Ω), but the reconstruction (α) arose as the next step only under human intervention, otherwise, this would have remained in poor condition. The evolution of adaptive loops formed by droughts, floods and countermeasures increased the resilience of the human–water relationship. Inhabitants took measures to prevent difficulties before problems occurred. Although floods and droughts were not always preventable, the gradual improvement of the human–water system caused this to be much more resilient in reaction to disasters.

The resilience loop may be described as a universal discipline, rather than only a regional phenomenon. Most of the world’s climate, topography and human activity are intertwined with precipitation and agriculture, and the human–water relationship is a core factor in an agricultural region. In the context of the uneven precipitation resulting from the monsoon, humans would likely constantly struggle

⁶ Yunnan Provincial Archives: No. 1077-001-07286-018, Consultation and reply to the Civil Affairs Department of Yunnan Province on the case of paying money to repair and dig the drainage river of Erhai Lake asked by Dengchuan county magistrate.

with different situations of flood and drought disasters. For example, drought and cold resistance could be the first obstacle to the development of agriculture in the low and medium plateau areas. Farming practices could be adopted to make up for the shortage of water conservancy engineering through the introduction of drought and cold resistant crops and sowing at appropriate times. Specific situations are highly variable from region to region, but the resilience of ecological environments that have been disturbed by human activities and the impacts of which have been mitigated by human maintenance mechanisms are two correlations that are crucial for the sustainability of regional ecology and society. It worth mention that the resilience has its ultimate limit and if it break the threshold, its rather hard or impossible to proceed to loop.

7. Conclusions

Developmental history of the Lake Erhai region shows that the basin was often subjected to floods and droughts. However, despite the floods and droughts, the early inhabitants still made great efforts to transform the central basin area from swamp to a 'land of fish and rice'. A set of farming methods that coped with cold, drought and flood hazards was developed for the higher hillside areas. Despite the pressure of the growing population, the region still achieved significant development and self-sufficient of food production in a long history.

In the relationship between humans and water in the Miju River Basin, problems continuously appeared but solutions were also implemented as society developed. Therefore, the water system of the Miju River Basin never collapsed and was further improved. The adaptive cycle phases of the water system were largely affected by human activities and could be modulated to a certain degree with front-loops or even back-loops. In other words, without human activities, such as water conservation works, the adaptive cycle of resilience could not loop upward but instead remained in an undesirable situation. Therefore, the renewal of water conservancy projects and the change of the water environment formed an upward circulation loop that continuously strengthened the resilience of inhabitants and water.

Therefore, the theory of adaptive cycles and resilience loops may be further elaborated by considering the factors of human activities when applied to a long-term human-environment evolutionary process. Humans are not often ineffectual in response to the changes in the natural environment, particularly if a set of effective measures is developed and an appropriate management framework is followed. The resilience loop theory may also be applied to broader areas or situations to provide deeper and more meaningful understanding, e.g. current

environment and water disaster responses, resilient urbanization and future climate change, adaptation and mitigations. Such as the water environment of Guizhou Plateau and Ba-shu Basin located at the southwest China had changed a lot, where were developed driven by the immigrants and urbanization. Moreover, some dry areas might be further investigated with the improved resilience loop theory, e.g. the Hexi Corridor in Northwest China, where the human-water relationship also faces challenges of population increase, climate change impacts, drought disasters, water pollutions, etc. Further exploration of the organizational mechanism and network effects of social groups, and developing modeling approaches to better reflect the evolutionary processes of human-water or human-environment relationships would be beneficial.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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