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**2nd World Heritage Irrigation Structures
Conference** organized by the Working Group on
History of Irrigation, Drainage and Flood Control (WG-HIST)

INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE
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Proceedings of the

International Workshop on
***2nd World Heritage Irrigation
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Preface



The International Workshop on World Heritage Irrigation Structures, organized by the Working Group on History of Irrigation, Drainage and Flood Control (WG-HIST) of the International Commission on Irrigation and Drainage (ICID), takes place in Marseille, France, on 13 October 2026, in conjunction with the 26th ICID International Congress and 77th International Executive Council Meeting. This volume brings together eight papers on the history, value and continuing use of irrigation systems.

Historic irrigation works are more than engineering remains. Many still deliver water, shape landscapes and support communities. Their conservation therefore calls for an understanding of how structures, local knowledge, institutions and present-day water needs fit together. The workshop offers a place to compare these relationships across regions and to consider how irrigation heritage can be sustained as conditions change.

The papers examine a wide range of systems and questions. Contributions from Japan explore the Kasai Yosui and the Tone River basin, relating historical water use to landscape, governance, flood control and agricultural development. Papers from China discuss ancient weirs and the relationship between irrigation engineering heritage and its natural and human setting. A study of meadow irrigation in Germany considers the ridge construction tradition in Suderburg. The volume also includes work on the revitalisation of the Douglas Weir in South Africa, the Beela-Batti system in India, and irrigation systems of the Zarafshon River basin. Together, these studies show that the value of irrigation heritage lies both in its historical record and in the choices, communities make about its future.

I hope these proceedings will encourage further exchange among researchers, engineers, heritage specialists and the people who manage these systems. I thank the authors for sharing their work, the participants for contributing to the discussion, and the members of WG-HIST and ICID who helped organize the workshop.

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FOLLOWING THE WATER — LANDSCAPE, REUSE, AND GOVERNANCE IN THE KASAI YOSUI, JAPAN

SUIVRE L'EAU: PAYSAGE, RÉUTILISATION ET GOUVERNANCE DANS LE KASAI YOSUI, JAPON

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ABSTRACT

The Kasai Yosui is one of Japan's largest and most historic agricultural water systems, drawing from the Tone River to irrigate lowland paddy landscapes northeast of Edo (present-day Tokyo) since the seventeenth century, and nominated for World Heritage Irrigation Structure designation by Japan's National Committee for ICID in 2026. This paper examines the Kasai Yosui as a socio-ecological system whose hydraulic design was conditioned by alluvial lowland topography, and considers the potential significance of its historically constituted water governance for modern water resource management, taking intersectoral water transfer as an illustrative case. The study draws on document-based historical and institutional analysis, including Edo-period records, existing historical analyses of Tone River basin hydraulic development, and institutional records of the Agricultural Water Reorganization Measures (AWRM) implemented from 1968.

The Kasai Yosui was developed in five stages between 1592 and 1719 using the Ina (Kanto) method, a hydraulic approach developed in response to the constraints of the alluvial lowland enclosed by the Tone, the Old Tone (the Present Edo), and the Old Iruma (the Present Arakawa) rivers, where the terrain made natural water intake to higher-lying paddies structurally difficult. Rather than controlling this topography, the Ina method worked with it: tame-i (shallow reservoirs) were constructed in old river channels to raise water levels and enable natural intake, while simultaneously capturing upstream drainage for downstream reuse. The resulting network inherently generated broad-area repetitive use, whereby drainage from upper paddies was collected and redistributed downstream — a basin-wide water recycling logic inseparable from the integrated flood control and irrigation design of the Ina method, giving the system its distinctly socio-ecological character. From 1968, the Kasai Yosui became one of Japan's earliest AWRM sites, with infrastructure modernization generating surplus water transferred to metropolitan waterworks. The institutional continuity provided by the Land Improvement District and the legal-administrative framework supporting water right conversion was among the conditions enabling this transition.

The Kasai Yosui offers an example of a traditional water reuse system in which the interplay of topography, hydraulic design, and governance institutions produced outcomes that remained relevant under modern conditions. The fact that intersectoral water transfer was achieved through historically constituted governance institutions — rather than requiring their replacement by centralized control or the dismantling of the existing water right framework — is itself noteworthy. Analysis of the conditions sustaining this continuity carries implications for heritage-sensitive water governance and for understanding the adaptive potential of traditional irrigation systems in contemporary water resource management.

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RÉSUMÉ

Le Kasai Yosui est l'un des systèmes d'irrigation agricole les plus importants et les plus anciens du Japon, alimenté par la rivière Tone pour irriguer les paysages de rizières des basses terres au nord-est d'Edo (l'actuel Tokyo) depuis le XVII^e siècle, et nominé pour le classement au Patrimoine mondial de l'irrigation par le Comité national japonais de la CIID en 2026. Cet article examine le Kasai Yosui en tant que système socio-écologique dont la conception hydraulique a été conditionnée par la topographie des basses terres alluviales, et considère la signification potentielle de sa gouvernance de l'eau historiquement constituée pour la gestion moderne des ressources en eau, en prenant le transfert intersectoriel de l'eau comme cas illustratif. L'étude s'appuie sur une analyse historique et institutionnelle documentaire, comprenant des archives de la période Edo, des analyses historiques existantes du développement hydraulique du bassin de la rivière Tone, et des archives institutionnelles des Mesures de Réorganisation des Eaux Agricoles (AWRM) mises en œuvre à partir de 1968.

Le Kasai Yosui a été développé en cinq étapes entre 1592 et 1719 selon la méthode Ina (Kanto), une approche hydraulique développée en réponse aux contraintes des basses terres alluviales enclavées entre la Tone, l'Ancienne Tone (l'actuelle Edo) et l'Ancien Iruma (l'actuelle Arakawa), où le terrain rendait structurellement difficile l'alimentation naturelle en eau des rizières en hauteur. Plutôt que de contrôler cette topographie, la méthode Ina a travaillé avec elle : des tame-i (réservoirs peu profonds) ont été construits dans d'anciens chenaux fluviaux pour élever les niveaux d'eau et permettre une prise d'eau naturelle, tout en capturant simultanément le drainage amont pour une réutilisation en aval. Le réseau ainsi constitué a engendré de manière inhérente une utilisation répétée à grande échelle, par laquelle le drainage des rizières supérieures était collecté et redistribué en aval — une logique de recyclage de l'eau à l'échelle du bassin, indissociable de la conception intégrée de contrôle des crues et d'irrigation de la méthode Ina, conférant au système son caractère distinctement socio-écologique. À partir de 1968, le Kasai Yosui est devenu l'un des premiers sites AWRM du Japon, la modernisation des infrastructures générant des eaux excédentaires transférées vers les réseaux d'eau municipaux. La continuité institutionnelle assurée par le District d'Amélioration Foncière et le cadre juridico-administratif soutenant la conversion des droits d'eau faisait partie des conditions permettant cette transition.

Le Kasai Yosui offre un exemple de système traditionnel de réutilisation de l'eau dans lequel l'interaction entre la topographie, la conception hydraulique et les institutions de gouvernance a produit des résultats restés pertinents dans les conditions modernes. Le fait que le transfert intersectoriel de l'eau ait été réalisé par le biais d'institutions de gouvernance historiquement constituées — plutôt que d'exiger leur remplacement par un contrôle centralisé ou le démantèlement du cadre existant des droits d'eau — est en soi remarquable. L'analyse des conditions maintenant cette continuité comporte des implications pour une gouvernance de l'eau respectueuse du patrimoine et pour la compréhension du potentiel adaptatif des systèmes d'irrigation traditionnels dans la gestion contemporaine des ressources en eau.

Keywords: Intersectoral water transfer; Agricultural Water Reorganization Measures (AWRM); socio-ecological system; repetitive water use; nested governance; heritage irrigation; Kasai Yosui

1. Introduction

Across rapidly urbanizing and industrializing regions worldwide, the transfer of water from agriculture to other sectors (intersectoral water transfer) remains a central issue in water resource management, and in recent years this has been increasingly discussed in relation to climate change adaptation and the design of water markets (Levine et al., 2007; Molle & Berkoff, 2009; Colby et al., 2011).

In Japan, Agricultural Water Reorganization Measures (AWRM) were implemented nationwide during the period of rapid economic growth in the 1960s and 1970s, against a backdrop of groundwater regulation in urban areas and surging water demand. A pioneering case was the series of projects (1968–2003) carried out in the Kasai Yosui area of the Tone River Basin (Matsuno et al., 2007). The Kasai Yosui is one of Japan's largest agricultural irrigation systems, developed between the sixteenth and eighteenth centuries, and was nominated by Japan's National Committee for ICID for World Heritage Irrigation Structure designation in 2026. From 1968, excess water generated by infrastructure

modernization was progressively transferred to municipal waterworks, making the Kasai Yosui an early model for intersectoral water transfer in Japan. While existing research has examined the technical and economic dimensions of this transfer in detail, this paper approaches the Kasai Yosui as a socio-ecological system in which topography, hydraulic conditions, and institutions are mutually interdependent, and asks what significance its historically constituted governance holds for water resource management today, using intersectoral water transfer as an illustrative case.

The analysis draws on documentary research, historical analysis, and a comparative case from Korea. The primary interpretation of historical sources is left to specialist historians; this paper instead takes existing research findings as given and conducts institutional and comparative analysis on that basis.

2. The Kasai Yosui in context: Alluvial lowland topography and hydraulic development

2.1 The alluvial lowland setting

The Kasai Yosui is an irrigation system that draws on the broad alluvial lowland formed by the Tone and Arakawa river systems. Specifically, it draws additional water from the Tone River while relying primarily on a chain of tame-i — shallow reservoirs formed by damming old river channels to raise water levels for irrigation intake and to collect drainage for reuse — built along the Furutone River (the former course of the Tone River, left without flow after a course diversion undertaken for flood control), which also serves as a combined irrigation and drainage channel. This lowland occupies the lowest-lying area enclosed by the Tone River (north), the Edo River (east), and the Arakawa River (west), formed by sediment deposited by rivers flowing down from the diluvial upland terrace to the northwest. The terrain therefore naturally collects water from these rivers, and apart from a few slightly elevated points on natural levees, it is a wetland chronically prone to poor drainage. At the same time, the land gradient is extremely flat at roughly 1/4,000 to 1/5,000. The former channels of the Tone and Arakawa rivers remained on the surface as shallow depressions, providing the topographic basis for the later construction of tame-i (Sato 1982; Kasai Irrigation Canal Land Improvement District, n.d.).

This topography created a fundamental constraint on irrigation. Because paddies typically lay higher than the canals supplying them, gravity-fed delivery was structurally difficult, making it essential to artificially raise water levels.

2.2 Staged hydraulic development and its defining features

The response to these topographic constraints was the Ina (Kanto) method, a hydraulic approach practiced across three generations of the Ina family, which for the first time made large-scale paddy conversion possible through the combination of flood control and new land reclamation. The Ina method can be characterized by three defining features (Sato 1982).

The first is the construction of tame-i in meandering river bends and former channels to secure water supply. By damming these channels to raise the water level, the method secured sufficient head for natural intake into lateral irrigation canals, converting the surrounding wetlands into paddy fields.

The second is the establishment of a distribution system that recycled upstream drainage as downstream irrigation water through the topography of former river channels. This logic of repetitive use was built into the design of the Ina method itself.

The third is flood management through kasumi-tei (discontinuous, open-ended levees) and retention basins, which accepted temporary flooding in exchange for fertile sediment deposition and soil moisture retention—framing flooding and agricultural production not as opposition but as coexistence (Sato, 1982; Ito 1949).

The Kasai Yosui was developed in five stages between the late sixteenth and early eighteenth centuries, proceeding from downstream to upstream, in response to existing topography. The system as a whole was not designed in advance, but should be understood as the cumulative result of each stage

responding to the hydrological and institutional challenges left by the one before it (Sato 1982; Koshigaya City 1978; Hashimoto 2002).

2.3 Comparison with the Minuma Daiyosui

The Minuma Daiyosui, a separate irrigation canal excavated in 1727, presents a contrasting design to the Kasai Yosui. Whereas the Ina method linked tame-i from downstream to upstream with drainage recycling built into the design, the Kishu method ran a newly constructed canal from upstream to downstream, keeping drainage (the Shiba River) and irrigation channels separate (Sato 1982).

Rather than competing, the two systems functioned complementarily within the same basin: surplus drainage from the Minuma Daiyosui was stored in tame-i of the downstream Kasai Yosui and reused as irrigation water. This pattern was not planned from the outset but emerged organically—an "emergent complementarity" that illustrates the regional character of the broad-area repetitive use discussed in detail in the following section.

3. The Ina (Kanto) Method and Broad-Area Repetitive Use

3.1 Tame-i: function and design logic

Tame-i are the structural core of the Kasai Yosui system. Siting them in former river channels was effective for two topographic reasons: these former channels lay lower than the surrounding land, making them natural collection points for drainage from surrounding paddies; and their width and depth allowed large volumes of water to be stored with relatively small weir structures. By raising the water level through damming, the design secured sufficient head for natural intake into lateral irrigation canals — resolving the problem of having no naturally elevated intake point.

Operating the irido — a sluice gate fitted to each tame-i — allowed managers to control the volume and timing of water released to each beneficiary area (Kasai Irrigation Canal Land Improvement District, n.d.; Sato 1982; Hashimoto 2002, pp.48–49).

What fundamentally distinguishes tame-i from simple diversion structures is their capacity to collect and reuse drainage. The tame-i store upstream return flow together with water drawn from the main river, functioning as recycling nodes. During periods when main river intake was restricted, this drainage-reuse function sustained supply downstream.

3.2 Broad-area repetitive use: mechanism and scale

Agricultural water in this system was managed under a broad-area repetitive use regime (Samura & Nakamura, 2004). Water drawn from the Tone River at Honkawamata repeats a cycle of intake, irrigation, drainage, recollection, and re-intake as it moves downstream. Across the Nakagawa basin, this repetitive use was estimated to occur up to six times for a given volume of water, with the total reused volume estimated at roughly 50 m³/s —exceeding both the customary water right of the Kasai Yosui (25.47 m³/s) and the intake volume of the Minuma Daiyosui (44.6 m³/s) (Yamazaki, 1985). The obligation placed on each water user to discharge drainage was therefore not merely a water-quality regulation, but an obligation built into the hydraulic system itself, necessary to maintain supply conditions for downstream users.

That AWRM was implemented in this broad-area, repetitive-use system carries important implications for how "excess water" should be conceptualized. A decline in paddy area does not automatically yield a corresponding volume of transferable water (Nagatsuka, 1983). The latent excess water became apparent — and transferable to urban use, only once infrastructure modernization reduced seepage and evapotranspiration losses. Realizing this potential also required the institutional conditions of infrastructure development and continuity of agency, discussed further below.

3.3 Integrated flood control and irrigation

The tame-i functioned simultaneously as flood retention basins and irrigation reservoirs, while kasumi-tei (discontinuous, open-ended levees) accepted temporary flooding in exchange for fertile sediment and soil moisture — a design that framed flooding and production as coexistence rather than opposed (Sato 1982; Ito 1949). This integration meant that the Kasai Yosui governance could not be discussed independently of river management.

Construction and maintenance by the shogunate were inseparable from its flood-control responsibilities, while day-to-day distribution and drainage management were carried out autonomously by water associations, forming a system of nested governance — a two-tier structure in which the shogunate bore responsibility for core infrastructure while local groups managed distribution and maintenance autonomously. Disputes over water and drainage were absorbed through reorganization at the district level without dismantling the system as a whole (Sato 1982; Hashimoto 2002; Koshigaya City 1978).

3.4 The system as a socio-ecological unit

The three features above — the tame-i as recycling nodes, broad-area repetitive use, and the integrated flood control and water use — are not independent technical traits but interdependent components of a single socio-ecological system. The structure in which topography, hydraulic design, and governance institutions sustain one another's function cannot hold if any one element is absent (Saito & Ichikawa 2014; Duraipappah et al. 2012). The Kasai Yosui's socio-ecological logic has persisted across political and institutional transitions— a persistence whose significance for modern water transfer is examined in the following sections.

4. Modern Water Transfer: AWRM as Illustrative Case

4.1 Background and preconditions

During the 1960s and 1970s, the Nakagawa basin in Saitama Prefecture underwent rapid urbanization. The population of the basin's 27 municipalities increased 2.58-fold, from 583,000 to 1,504,000, between 1960 and 1980, while paddy area declined from 41.4% to 35.8% of land use (Yamazaki, 1985). On the urban side, water demand grew sharply, while groundwater pumping was regulated as a countermeasure to land subsidence, forcing a shift from groundwater to surface water. On the agricultural side, structural changes in village communities increased the burden of canal maintenance, creating a need for new irrigation facilities and management systems (Minegishi, 2003; Sato et al., 1979).

Against this backdrop, a policy direction emerged toward transferring excess water to urban use. The AWRM addressed in this paper involves the modernization of agricultural irrigation infrastructure to generate transferable excess water. Rising costs for new dam construction made this option comparatively cost-effective, and the relatively modest water volumes involved (averaging 0.8 m³/s) allowed flexible, suburban implementation with a shorter development period than dam construction (Kimizuka, 1978). In 1962, the Tone River basin was designated under the Water Resources Development Promotion Act, establishing the policy framework within which agricultural water rationalization was progressively pursued (Wakisaka, 1983).

4.2 Stage I (1968–1972): Main Canal Modernization

This project — the first full-scale prefecturally funded AWRM in Japan — rehabilitated the Kasai Yosui main canal (lining and consolidating diversion outlets), installed water-level control gates, and reorganized water supply by rehabilitating the Kitagawa irrigation canal to incorporate the Gongendo beneficiary area into the Kasai Yosui system. The 5.475 m³/s water right formerly held for the Gongendo canal was transferred to urban use, with 2.666 m³/s going to the Saitama Prefectural Waterworks (Minegishi, 2003; Wakisaka, 1983; Matsuno et al., 2007). The total project cost of JPY 2.01 billion was borne entirely by the Saitama Prefecture Public Enterprise Bureau. This project also prompted the

conversion of the Kasai Irrigation Canal LID's water right from customary to legal status — the standard procedure for all subsequent AWRM projects (Matsuno et al., 2007).

4.3 Stage II (1973–1987): pipeline system

Stage II extended modernization to terminal facilities, installing pipelines, farm ponds, check gates, and a central control across the Gongendo (1,212 ha) and Satte (1,913 ha) areas. A total of 1.581 m³/s was transferred to urban use. The total project cost was JPY 20.9 billion, shared 26.7% by the agricultural sector and 73.3% by the urban sector; through negotiation, the urban sector also assumed the farmers' share and post-project O&M costs, leaving farmers with no net financial burden (Matsuno et al., 2007).

4.4 National AWRM and subsequent stages

The third project (the Saitama Gokuchi Stage II project, 1978–1994) transferred 3.067 m³/s, and the fourth (Tone Chuo project, 1992–2003) transferred 3.811 m³/s, securing water supply for roughly 650,000 people. The total project cost was JPY 38.7 billion and JPY 70.4 billion respectively, shared approximately equally between agricultural and urban sectors (Matsuno et al., 2007). Between 1965 and 2001, a total of 71.6 m³/s was transferred from agriculture nationwide, with the Tone River basin as the central case.

4.5 Enabling conditions: what made transfer possible

Three conditions converged to make AWRM possible in the Kasai Yosui area. The first is hydrological: the broad-area repetitive-use system created a structure in which latent excess water could arise, becoming transferable through infrastructure modernization. The second is institutional: by retaining its customary water right, the LID functioned as an equal party in negotiations, producing an exchange in which the urban side (the Saitama Prefecture Public Enterprise Bureau) bore infrastructure costs, while the agricultural side (the LID) agreed that part of its water right would be held by the Japan Water Agency (JWA). The third is historical continuity: the nested governance that took its most developed form during the Edo period — the shogunate bearing responsibility for core infrastructure while local associations carried out day-to-day distribution and maintenance — continued in the form of water associations and, later, land improvement districts, providing a consistent institutional counterpart throughout transfer negotiations and proving compatible with the cost-sharing structure of AWRM.

5. Discussion

AWRM in the Kasai Yosui area was made possible by the convergence of three conditions: hydrological, institutional, and historical continuity. This section examines the significance of the institutional condition — the role of the LID as a water management agency — through contrast with the reorganization of agricultural water governance in Korea.

In 2000, the Korea Agricultural & Rural Infrastructure Corporation (now the Korea Rural Community Corporation, KRC) was established through the merger of agricultural land improvement associations, abolishing the irrigation association fee and transferring water rights from farmers to the KRC (Shin et al., 2012). This consolidation achieved nationwide unification of the water management and improved maintenance standards. At the same time, it led farmers to lose their willingness to participate in water management (Lee et al., 2010), and for intersectoral water transfer in particular, a different pattern of outcomes has been recorded: farmers who opposed the transfer had no formal legal recourse, as water rights now belong to the KRC.

In the Kasai Yosui, by retaining its customary water rights, the LID was able to function as an equal party in transfer negotiations — an agency-based approach that Shin et al. (2012) implicitly endorse when concluding that the Korean case calls for the restoration of farmer participation rather than further centralization. The broader implication is that the success of intersectoral water transfer depends not only on technical and economic conditions, but on who holds agency in the institutional framework

governing water rights and cost-sharing. Agricultural water should not be treated as a surplus resource available for immediate transfer, but rather requires a gradual transition supported by improved monitoring and collaborative governance among stakeholders (K. Yoon, personal communication, 2026).

6. Conclusion

The development of AWRM in the Kasai Yosui should be understood not merely as a product of technical modernization, but as the result of converging hydrological, institutional, and historical conditions. The existence of latent excess water made possible by a broad-area, repetitive-use system formed a necessary hydrological condition; the LID's continued agency as the maintenance authority constituted the institutional condition; and the persistence of nested governance — which preserved agency despite change, carried forward through the postwar institution of the land improvement district — constituted the condition of historical continuity. Together, these formed the structural background that made the transfer possible.

The contrast with the Korean case shows that water transfer depends not only on technical and economic conditions, but deeply on the institutional framework — on who bears the cost of maintaining water infrastructure and how that cost is valued, and on how methods for measuring hydrological conditions, including excess water, and consensus around them, are established.

Water follows topography, follows institutions, and follows history. What the Kasai Yosui demonstrates is a simple but easily overlooked fact: that technical solutions in modern water resource management emerge from, and depend on, an ongoing interplay with the institutional and historical foundations that sustain them.

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COUPLING-MECHANISM BETWEEN IRRIGATION-ENGINEERING HERITAGE AND NATURAL-HUMANISTIC ENVIRONMENT

MÉCANISME DE COUPLAGE ENTRE LE PATRIMOINE DES OUVRAGES D'IRRIGATION ET L'ENVIRONNEMENT NATUREL ET HUMANISTE

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ABSTRACT

Irrigation-engineering heritage is a living social-ecological compound system integrating engineering technologies, natural endowments and regional socio-cultural elements. To reveal the internal mechanism enabling ancient irrigation facilities to operate for thousands of years amid climate fluctuations and social transformations, this paper selects typical World Heritage Irrigation Structures in China as empirical cases. Adopting the system-coupling theory, it establishes a three-dimensional analytical framework covering engineering-natural coupling, engineering-social coupling and dynamic adaptive coupling, so as to interpret the coupling paths and functional mechanisms between irrigation-engineering heritage and the natural-humanistic environment. The study shows that engineering-natural coupling advocates construction in compliance with local water-soil conditions and realizes symbiosis between man-made facilities and natural environments via indigenous technologies. Engineering-social coupling provides non-material supports for long-term operation of projects through water-right institutions, community self-governance, local conventions and livelihood-related cultures. Dynamic adaptive coupling promotes iterative updates of engineering measures and management systems while upholding core technical values, and achieves the resilience-oriented evolution of the whole system. The balanced maintenance of the three types of coupling relationships constitutes the fundamental reason for the living continuity of irrigation heritage. Based on the coupling mechanism, three principles for sustainable living-heritage conservation are put forward: priority of functional continuity, holistic system-oriented conservation, and dynamic adaptive conservation. This research argues that the long-term vitality of irrigation-engineering heritage stems from the resilience of the complete social-ecological system rather than the physical durability of building materials. Traditional hydraulic ecological knowledge and local water-governance experience can offer historical references for global water-heritage governance and hydraulic-resilience construction against climate change. Nevertheless, traditional wisdom shall be critically inherited under contemporary social conditions to reconstruct man-water coupling relationships adaptable to modern-day development.

RÉSUMÉ

Le patrimoine des ouvrages d'irrigation est un système socio-écologique vivant et composite, intégrant les technologies d'ingénierie, les atouts naturels et les éléments socioculturels régionaux. Afin de révéler le mécanisme interne permettant aux anciens ouvrages d'irrigation de fonctionner pendant des millénaires malgré les fluctuations climatiques et les transformations sociales, cet article retient comme cas empiriques des ouvrages d'irrigation inscrits au Patrimoine mondial de l'UNESCO en Chine. S'appuyant sur la théorie du couplage systémique, il établit un cadre d'analyse tridimensionnel qui recouvre le couplage ouvrage-nature, le couplage ouvrage-société et le couplage adaptatif dynamique, pour interpréter les voies de couplage et les mécanismes fonctionnels entre le patrimoine des ouvrages d'irrigation et l'environnement naturel et humaniste. L'étude montre que le couplage ouvrage-nature préconise une construction adaptée aux conditions locales de l'eau et du sol, et réalise la symbiose entre les ouvrages artificiels et les milieux naturels au moyen de savoirs endogènes. Le couplage ouvrage-société apporte un soutien immatériel au fonctionnement pérenne des aménagements, à

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travers les institutions relatives aux droits de l'eau, l'autogouvernance communautaire, les coutumes locales et les cultures liées aux modes de subsistance. Le couplage adaptatif dynamique favorise l'actualisation itérative des mesures techniques et des systèmes de gestion tout en préservant les valeurs techniques fondamentales, et permet l'évolution du système global orientée vers la résilience. Le maintien équilibré de ces trois types de relations de couplage constitue la raison fondamentale de la continuité vivante du patrimoine d'irrigation. Sur la base de ce mécanisme de couplage, trois principes de conservation durable du patrimoine vivant sont proposés : la priorité de la continuité fonctionnelle, la conservation systémique holistique et la conservation adaptative dynamique. Cette recherche soutient que la vitalité à long terme du patrimoine des ouvrages d'irrigation provient de la résilience du système socio-écologique complet, plutôt que de la seule durabilité physique des matériaux de construction. Les savoirs écologiques hydrauliques traditionnels et les expériences locales de gouvernance de l'eau peuvent offrir des références historiques pour la gestion mondiale du patrimoine hydraulique et la construction de la résilience hydraulique face au changement climatique. Néanmoins, ces sagesses traditionnelles doivent être reprises de manière critique dans le contexte social contemporain, afin de reconstruire des relations de couplage homme-eau adaptées aux développements modernes.

Keywords: Irrigation-engineering heritage; Coupling mechanism; Living heritage; social-ecological system; World Heritage Irrigation Structures

1. Introduction

Irrigation civilization lays the fundamental support for the formation and development of agricultural civilization. Irrigation-engineering heritage preserves technical wisdom and social-governance experience accumulated by humans in coping with flood-drought disasters and exploiting water-soil resources across diverse regions. Different from static archaeological relics, World Heritage Irrigation Structures are typical living heritage. A large number of such heritage sites still perform functions including agricultural irrigation, ecological regulation and people's livelihood guarantee, with constant interactive evolution among engineering structures, hydrological systems, local communities and folk cultures. A scientifically thought-provoking question for academia is: how could some irrigation facilities built thousands of years ago sustain operational efficiency across millennia under multiple shocks such as climate fluctuation, geomorphic evolution and institutional transition.

Global understanding of living irrigation-related heritage has been gradually advanced. In 2002, the Food and Agriculture Organization of the United Nations (FAO) launched the Globally Important Agricultural Heritage Systems (GIAHS) initiative, establishing an evaluation framework for living agricultural systems and emphasizing that heritage cannot exist in isolation from local community production and livelihood. In 2014, the International Commission on Irrigation and Drainage set up the World Heritage Irrigation Structures programme, developing specialized assessment, nomination and conservation systems for irrigation-engineering heritage, which marked its establishment as an independent international heritage category. China boasts a time-honoured irrigation civilization, and diverse technical paradigms of irrigation have been cultivated in varied physiographical units, jointly forming the pluralistic panorama of Chinese irrigation heritage.

Existing domestic studies can be categorized into three groups. The first focuses on textual research of engineering-technical history, restoring structural layouts, construction techniques and historical evolution of individual heritage sites from a technical perspective. The second is oriented toward heritage value assessment and tourism-oriented exploitation, concerning cultural values and industrial transformation paths. The third explores living-heritage conservation strategies mostly based on case-specific experience. On the whole, current literature pays insufficient attention to the intrinsic correlations among engineering structures, natural environments and socio-cultural dimensions. It fails to uncover the underlying mechanism behind the millennial survival of irrigation-engineering heritage from a systematic-coupling perspective, and lacks general theoretical frameworks built upon multi-case comparisons. Some studies equate irrigation-engineering heritage with ancient hydraulic architectures and reduce conservation work to restoration of ancient buildings, ignoring the complete social-ecological system behind heritage sites.

Given the above research gaps, this paper takes representative Chinese World Heritage Irrigation Structures as research objects, introduces system-coupling theory and constructs a three-dimensional coupling analytical framework. Through multi-case empirical analysis, it interprets coupling paths between irrigation-engineering heritage and natural-humanistic environments, clarifies functional mechanisms of different coupling types, extracts theoretical principles for sustainable living-heritage conservation, and explores implications of traditional water-governance wisdom for modern water-resource administration and climate-resilience construction.

2. Core Concepts and Analytical Framework

2.1 Connotation of Coupling and Its Applicability for Irrigation-Heritage Research

Derived from system science, coupling refers to the status of mutual interaction, restriction and interdependence among two or more independent systems. Systems exchange elements via material flow, energy flow and information flow, and further constitute an integrated compound system. When coupling relationships maintain sound equilibrium, the stability of the compound system improves. Once coupling chains break down, functional degradation or even total collapse of the system may occur.

Irrigation-engineering heritage is a compound system superposed by the natural subsystem-engineering subsystem-socio-cultural subsystem. The natural subsystem covers hydrology, topography, geology, climate and other elements. The engineering subsystem consists of man-made structures such as dykes, canals, reservoirs, underground tunnels and sluice-weirs. The socio-cultural subsystem includes water-right institutions, community organizations, local conventions, sacrificial beliefs and production-livelihood patterns. Instead of simple superposition, the three subsystems realize deep integration through coupling mechanisms. This paper summarizes three core coupling relationships: engineering-natural coupling, engineering-social coupling, and dynamic adaptive coupling.

Engineering-natural coupling describes interactions between man-made irrigation projects and regional hydrological-geological-topographic-climatic conditions. Its core proposition lies in how projects are constructed in compliance with natural endowments, reducing forcible transformation of nature and achieving coordinated coexistence between engineering works and water-soil environments rather than conquering natural conditions.

Engineering-social coupling denotes intrinsic connections between irrigation infrastructures and social institutions, community organizations, folk customs as well as local livelihoods. Hydraulic structures merely provide material hardware, whereas non-material elements including water allocation, maintenance obligations, dispute settlement and value identity determine long-term project operation. It addresses how to realize harmonious human-water co-governance.

Dynamic adaptive coupling represents the self-regulating capacity of the whole irrigation-heritage compound system confronted with external disturbances such as climate change, geomorphic evolution and social-structural transformation. The system adheres to its core values while iterating specific engineering measures and management institutions to achieve continuous self-renewal. The millennial living continuity of irrigation-engineering heritage relies on the equilibrium of the three coupling relationships. Failure of any single coupling chain will lead to system decline.

Table 1. Three Coupling Mechanisms of Irrigation-Engineering Heritage

Coupling Type	Core Relationship	Key Scientific Question
Engineering-natural coupling	Irrigation infrastructures ↔ hydrological- geological-topographic conditions	How to utilize rather than counteract natural endowments?
Engineering-social coupling	Irrigation infrastructures ↔ institutions-communities-cultures-livelihoods	How to build an orderly social system for water governance?
Dynamic adaptive coupling	Irrigation compound system ↔ changing internal and external disturbances	How to realize long-term self-renewal and resilience of the system?

2.2 Criteria for Case Selection

To guarantee the universality of research conclusions, cases are selected from nominated World Heritage Irrigation Structures covering typical Chinese physiographical units with diversified engineering patterns, namely Dujiangyan, Sakya Irrigation System, Xinghua Duotian Raised-Field System and Turpan Karez. Dujiangyan represents large-scale dam-less water-diversion projects in monsoon basins. Sakya Irrigation System stands for irrigation works in high-altitude frigid zones. Xinghua Duotian Raised-Field System is an agro-irrigation compound system with artificially reconstructed micro-landforms in low-lying waterlogged plains. Turpan Karez is a folk-governed underground hydraulic project in arid desert regions. The selected cases cover both state-sponsored construction and spontaneous folk construction modes, which can fully demonstrate performances of the three coupling mechanisms under varied scenarios.

3 Empirical Analysis on Multiple Coupling Mechanisms of Irrigation-Engineering Heritage

3.1 Engineering-Natural Coupling: Following Natural Trends To Build Co-Existence Between Projects And Water-Soil Environments

The essence of engineering-natural coupling is to adjust measures to local conditions. Natural conditions serve as pre-constraints for engineering design. Full use shall be made of topographic relief, hydraulic characteristics, sunlight, temperature and other natural resources to cut construction-operation costs, prevent hydrological-geological hazards, and enable smooth material-energy exchange between artificial and natural systems.

Constructed in 256 BCE on the Minjiang River alluvial fan, Dujiangyan was threatened by high sediment loads and seasonal floods endangering the Chengdu Plain. Adopting a dam-less diversion scheme with three principal structures: Fish-Mouth Dyke, Feisha-Weir Spillway and Baopingkou Water Inlet, Dujiangyan accomplishes water diversion, sediment evacuation and flood discharge by leveraging river hydrodynamics. The annual maintenance rule of “deep dredging, low weir” incorporates siltation into system circulation. Standardized winter dredging is implemented annually to guarantee canal conveyance capacity. Gravity-driven water conveyance takes advantage of natural topographic relief of the Minjiang River without extra energy input. Instead of blocking river runoff forcibly, the whole project diverts water and sediment following natural flows, which constitutes a classic paradigm of engineering-natural coupling.

Located on the Qinghai-Tibet Plateau above 4 000 m above sea level, the Sakya Irrigation System suffers from core environmental stresses including frost heave damage, canal icing, excessively cold snow-melt water and massive heat loss in winter with minimum temperature down to -25 °C. Local ancestors developed a technical system adapted to alpine-frigid environments: first, rectangular open reservoirs absorb plateau solar radiation to warm cold snow-melt water for irrigation; second, steep-gradient canals make use of terrain drop to accelerate flow velocity and mitigate icing risks; third, canal beds are lined with dark stone slabs for seepage control and thermal preservation to retard ice formation and ensure long-distance water conveyance under frigid conditions. Fully responding to alpine constraints, such indigenous techniques demonstrate prominent adaptability under extreme environments.

Situated in the low-lying lake-marsh zone of the Lixiahe Region between the Yangtze and Huaihe Rivers, the Xinghua Duotian Raised-Field System faces frequent waterlogging where original water-soil conditions hardly support large-scale farming. Local residents dredge river-lake silt and pile it up to build elevated mounds above water surfaces. Crops are planted on mounds while ditches among mounds undertake water conveyance, drainage and navigation functions, forming the unique man-made micro-landscape of “island-like farmlands on water”. Human beings mitigate flood hazards by reconstructing local micro-topography and realize sustainable agricultural production in waterlogged areas.

Turpan Karez adapts to extreme arid northwest environments where evaporation far exceeds precipitation. Open-canal conveyance would cause tremendous water loss. Ancestors excavated underground tunnels to capture piedmont groundwater, minimizing evaporative water consumption. Combined with vertical shafts, underground tunnels constitute distinctive underground irrigation networks for arid zones, representing a great creation of projects adapting to desert natural settings[2]. Above cases indicate that successful traditional irrigation projects do not reshape nature to satisfy human demands. Instead, engineering schemes are adjusted to fit natural endowments, which forms the core connotation of engineering-natural coupling.

3.2 Engineering-Social Coupling: Empowerment From Institutions, Communities And Cultures To Sustain Social Order For System Operation

Complete hydraulic structures merely provide material foundations for heritage survival. Without supporting social-governance systems, even finished projects cannot operate sustainably. Engineering-social coupling means irrigation projects are deeply embedded within local social fabrics. Non-material supporting systems are formed via water-right institutions, community self-governance, local conventions, livelihood patterns and water-related beliefs, to fulfil multiple social functions including water allocation, facility management-maintenance, water-dispute settlement and community-value shaping. It is an indispensable prerequisite for living inheritance of irrigation heritage.

Turpan Karez serves as a typical example of engineering-social coupling under folk self-governance. Its management traditions are deeply rooted in village customs. Stable contractual relationships are forged between hydraulic infrastructures and local societies, with relevant legends and conventions internalized into community collective mindsets, endowing it with outstanding historical-cultural and anthropological values. From the Qing Dynasty to the Republic of China, two parallel management systems were established: official karez and folk karez. Folk karez followed the principle of “whoever builds owns it”. Folk water rights were officially protected, and canal maintenance obligations were shared by all water beneficiaries. Water-related responsibilities were explicitly stipulated in land-tenancy contracts. Official karez were funded and operated by governments. In 1916, Yang Zengxin, Governor of Xinjiang Province, presided over the restoration of abandoned karez in Turpan, advocating renovating old karez rather than digging new ones. Special financial appropriations were allocated by provincial finance authorities, and an official hand-over system was implemented: outgoing magistrates should hand over inventories of karez quantity and fund revenues-expenditures to successors. At the folk level, mature self-governance mechanisms took shape: water rights could be sold, purchased, inherited and transferred; water was allocated precisely according to water-using time slots or cultivated land areas; villagers took turns undertaking annual silting-removal work known as “taolao”; water-related disputes were mediated via local conventions without official intervention. As material carriers, underground tunnels are deeply integrated with property-right, labour and mediation institutions. Folk legends further consolidate community consensus, jointly sustaining long-term operation of Karez.

Xinghua Duotian Raised-Field System reflects the coupling path of mutual empowerment between livelihood and heritage. It obtains dual designations both as World Heritage Irrigation Structure and Globally Important Agricultural Heritage System. Local authorities develop the Rape-Flower Festival based on its agricultural landscapes to promote agro-heritage tourism. Tourism revenues feed back into ditch dredging and mound maintenance. Local farmers act both as agricultural producers and heritage guardians. Livelihood benefits are closely bound up with heritage survival. Heritage conservation is transformed from one-sided administrative tasks imposed by governments into endogenous community demands, achieving mutual gains of livelihood improvement and heritage preservation.

Water-management stone steles preserved in ancient irrigation zones constitute tangible carriers of engineering-social coupling. Inscriptions on steles record water-allocation quotas, annual-maintenance labour obligations and penalties for damaging hydraulic facilities. Oral folk conventions are solidified into public contracts, clarifying “who uses water, when to use water and how much water can be used” so as to mitigate water conflicts. Supporting water-deity-worshipping systems were developed. Historical hydraulic figures such as Li Bing were deified. Temples were built for sacrifices together with opening-canal ceremonies. Sacrificial rituals strengthen collective community identity and turn

hydraulic-facility maintenance into moral obligations shared by communities. Physical projects offer water-conveyance carriers; institutions define behavioural norms; cultural beliefs generate motivation for collective actions. The three dimensions jointly realize engineering-social coupling.

To sum up, irrigation-engineering heritage cannot survive independently from its social context. Only deeply embedded in community organizations, property-right regimes and regional cultures with multi-dimensional social supports can irrigation-engineering heritage achieve long-term living inheritance.

3.3 Dynamic Adaptive Coupling: Balancing Continuity and Change for Resilient Evolution of Compound Systems

Natural-social-economic conditions keep changing constantly. External disturbances such as sediment accumulation, flood impacts, climate fluctuations, demographic shifts and institutional reforms exert pressures on irrigation systems. Static projects cannot cope with continuous environmental changes. Millennial-surviving irrigation heritage generally possesses dynamic adaptive-coupling capacity: under the premise of preserving core technical principles and value connotations, engineering measures and management regimes are iteratively adjusted to strike a balance between continuity and change.

Dujiangyan exemplifies dynamic adaptive coupling. Over more than two thousand years, its core technical principles remain stable: adhering to the dam-less diversion pattern, inheriting the annual-maintenance doctrine of “deep dredging, low weir”, and passing down man-water-harmony wisdom from generation to generation. Nevertheless, specific engineering and managerial practices keep evolving: irrigation districts expand alongside population growth; sluices and overflow facilities are upgraded to satisfy practical demands; administrative regimes are reformed repeatedly from ancient weir-official systems to modern hydraulic authorities. Core hydraulic wisdom is inherited while engineering and management tools keep pace with times, enabling Dujiangyan to withstand multiple disturbances including floods, siltation and social transformations.

Dynamic adaptive coupling reveals a common misconception in living-heritage conservation: living-heritage protection does not mean “freezing” heritage at a certain historical time slice or replicating all ancient structures strictly. The genuine conservation goal is to maintain the adaptive capacity of the whole system and guarantee continuous functional operation. Rational technical updates are permissible for heritage systems as long as core values and coupling logics are not undermined.

4 Principles for Sustainable Conservation of Irrigation-Engineering Heritage Derived From Coupling Mechanisms

The three coupling mechanisms interpret the intrinsic logic behind the millennial survival of irrigation-engineering heritage and provide theoretical foundations for contemporary conservation. Traditional cultural-relic conservation often focuses on restoring hydraulic structures alone, which tends to break coupling chains among engineering-nature-society and results in dilemmas of “physical projects exist without functions; relics are preserved yet communities vanish”. Based on coupling theories, three sustainable conservation principles for irrigation-engineering heritage are proposed.

First, prioritize functional continuity and reject form-oriented frozen conservation. For living irrigation heritage, practical functions including irrigation and flood regulation constitute its source of vitality. Once operational functions are artificially terminated and only static architectures are reserved, both engineering-natural and engineering-social coupling chains will fracture, and core living-heritage values will disappear. Conservation shall prioritize functional performance. “Being in service” itself represents the most efficient conservation approach. Pursuit of superficial antique appearances shall not override practical system performance.

Second, uphold holistic system-oriented conservation and transcend single-component-centred thinking. Irrigation-engineering heritage is not equivalent to isolated constructions such as dykes and sluices. Conservation objects shall cover the whole compound system: physical infrastructures including

canals, reservoirs and sluice-weirs; natural elements such as hydrological networks and topographic features; non-material dimensions covering water-right institutions, local conventions, folk sacrifices, indigenous knowledge and community livelihoods. Protecting individual hydraulic structures while ignoring hydrological environments and community institutions essentially severs coupling relationships and fails to safeguard authentic living-heritage values.

Third, advocate dynamic adaptive conservation and oppose chronological freezing. Living heritage itself is an evolving system. Its legitimate evolutionary rights shall be respected. Conservation work shall preserve core technical ideas and value connotations. Moderate renovation of infrastructures and management institutions is allowed to adapt to modern-day social-economic demands. The conservation objective is to sustain systemic resilience rather than fix heritage to a certain historical period.

5 Research Implications and International Reference Value

Research on coupling mechanisms of Chinese irrigation-engineering heritage offers multiple inspirations for global water-heritage governance and revitalization of traditional ecological knowledge.

Firstly, traditional hydraulic ecological knowledge bears contemporary practical values. The underground-tunnel mode of Karez realizes zero-energy groundwater exploitation and provides historical references for high-efficiency water-resource utilization in global arid zones. Abandoning high-dam-large-reservoir concepts, Dujiangyan adopts minimalist low-intervention configurations to realize multi-functions including water diversion, flood discharge, sediment evacuation and irrigation. It interprets the governance philosophy of maximizing comprehensive benefits with minimum engineering costs and sheds light on integrated river-basin management. Against the background of global climate change, frequent extreme events such as heatwaves, cold surges, droughts and floods call for new thinking on modern hydraulic resilience, which can be enlightened by millennial-tested resilience experience of Chinese irrigation heritage surviving temperature ranges from -25°C to 40°C .

Secondly, community-participatory water governance has profound historical roots. The millennial operation of Karez relies on folk self-governance, and water-allocation contracts inscribed on stone steles demonstrate that community participation is not a modern-day governance concept. Indigenous water-right, labour-management and dispute-mediation institutions in rural societies can serve as effective instruments for water administration, offering historical references for irrigation-management reforms in arid and semi-arid regions worldwide.

Furthermore, heritage is more than historical relics but resources oriented toward a sustainable future. Conservation of irrigation-engineering heritage is not merely for preserving ancient cultural memories, but for exploring systematic wisdom of human-water symbiosis. Irrigation heritage shall not be treated as mere tourist attractions. Creative transformation of traditional technologies and governance knowledge should be promoted to support modern-day water-security construction and ecological civilization development.

Meanwhile, limitations shall be objectively recognized: traditional coupling mechanisms were formed under ancient productivity conditions. Great changes have taken place in contemporary population scale, land-use patterns and water-resource pressures. Blind copy of ancient modes should be avoided. Traditional wisdom shall be critically inherited combined with modern hydraulic technologies to reconstruct man-water coupling relationships compatible with modern-day society.

6 Conclusions

The millennial living continuity of irrigation-engineering heritage does not depend on the physical robustness of stone materials of hydraulic structures. Its root lies in social-ecological-system resilience jointly constructed by engineering-natural coupling, engineering-social coupling and dynamic adaptive coupling. Engineering-natural coupling achieves symbiosis between artificial facilities and water-soil environments. Engineering-social coupling provides social supports for system operation via water-right

institutions, community self-governance, livelihood communities and folk beliefs. Dynamic adaptive coupling realizes systemic self-renewal while preserving core values. The three types of coupling are indispensable and together constitute the survival code of irrigation heritage.

When irrigation projects achieve dynamic balance with rivers, sediment and climate, and are deeply embedded in community bonds, local covenants and cultural beliefs, heritage will transcend physical limits of structures and evolve into foundational carriers of civilization. Conserving irrigation-engineering heritage is not simply looking back to the past, but extracting human-water-symbiosis wisdom embedded in heritage sites to seek historical inspirations for coping with modern-day water-resource crises and climate-change challenges.

For future conservation practices in China, we should break away from the path of “over-emphasis on physical structures while neglecting systematic contexts; preference for static restoration over living operation”. The three principles of function priority, holistic-system conservation and dynamic adaptation shall be implemented. Natural-ecological elements, engineering entities, community livelihoods and institutional-cultural dimensions shall be coordinated to realize long-term living inheritance of irrigation-engineering heritage.

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HERITAGE VALUE OF IRRIGATION SYSTEMS IN THE TONE RIVER BASIN, JAPAN: LINKING EARLY MODERN WATER USE, FLOOD CONTROL, AND AGRICULTURAL DEVELOPMENT

VALEUR PATRIMONIALE DES SYSTÈMES D'IRRIGATION DU BASSIN DU TONE, JAPON : EAU, LUTTE CONTRE LES INONDATIONS ET DÉVELOPPEMENT AGRICOLE AU DÉBUT DE L'ÉPOQUE MODERNE

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ABSTRACT

The Tone River basin in eastern Japan played a central role in the historical development of the Kanto Plain, including the growth of Edo and the expansion of one of Japan's major agricultural regions. During the early modern period, river-course modification, flood control, irrigation development, drainage improvement, and reclamation progressed in close interaction. Today, six irrigation systems in the Tone River system are recognised as World Heritage Irrigation Structures (WHIS).

This paper reviews the historical development of major irrigation systems in the basin, focusing primarily on the late sixteenth to eighteenth centuries, using Japanese historical syntheses, previous studies, and official documentation. Irrigation development did not follow a single linear pathway: long-established local systems coexisted with large early-Tokugawa canals, while lowland networks incorporated former river channels, storage, drainage, and repeated water reuse. During the Kyōhō period, newer projects introduced long-distance diversion, clearer separation of irrigation and drainage, and reclamation, yet earlier systems continued to function and in some cases became hydrologically connected with them. The heritage significance of the Tone River irrigation systems therefore lies not only in individual structures but also in the layered historical process through which hydraulic infrastructure, agricultural landscapes, and water-management institutions developed in relation to one another.

RÉSUMÉ

Le bassin du Tone, dans l'est du Japon, a joué un rôle central dans le développement de la plaine du Kanto, notamment dans l'essor d'Edo et l'expansion agricole. Au début de l'époque moderne, modification des cours d'eau, lutte contre les inondations, irrigation, drainage et mise en valeur des terres ont progressé conjointement. Aujourd'hui, six systèmes d'irrigation du réseau du Tone sont reconnus comme World Heritage Irrigation Structures (WHIS). Cet article examine les systèmes d'irrigation du bassin entre la fin du XVI^e et le XVIII^e siècle à partir de synthèses japonaises, d'études antérieures et de documents officiels. Le développement de l'irrigation n'a pas suivi une trajectoire linéaire : des systèmes locaux anciens ont coexisté avec de grands canaux du début de l'époque Tokugawa, tandis que les réseaux de plaine ont intégré anciens chenaux, stockage, drainage et réutilisation de l'eau. Durant l'ère Kyōhō, de nouveaux aménagements ont introduit des dérivations à longue distance, une séparation plus nette entre irrigation et drainage et la mise en valeur des terres, sans remplacer les systèmes antérieurs. La valeur patrimoniale réside ainsi dans les ouvrages individuels comme dans le processus historique stratifié reliant infrastructures hydrauliques, paysages agricoles et institutions de gestion de l'eau.

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1. Introduction

The Tone River is one of the principal rivers of Japan and has played a major role in the historical development of the Kanto Plain. Before the early modern period, the river flowed generally southwards across the plain towards Tokyo Bay. From the late sixteenth through the seventeenth century, successive engineering works progressively altered the courses and connections of the Tone River and its major tributaries (Musiake, 1988; Tamaki, 1984). These interventions, commonly discussed collectively as the eastward diversion of the Tone River, were not a single project undertaken at one time or for one purpose. Musiake (1988) identified transportation, land reclamation, military defence, and flood protection among the purposes of these historical river works, while Japanese historical syntheses place them within a broader process of regional and agricultural transformation (Sato, 1982; Tamaki, 1984). Recent hydrological modelling has further demonstrated the importance of the reconstructed river network in increasing low flows along inland navigation routes linking the Kanto region with Edo, present-day Tokyo (Trošelj and Hanasaki, 2025).

Agricultural development formed an integral part of this transformation. Much of the central and eastern Kanto Plain consisted of low-gradient alluvial land crossed by unstable river channels, wetlands, and former channels. Flooding and poor drainage constrained stable cultivation, while small differences in local elevation frequently complicated gravity-fed irrigation. Japanese historical studies therefore describe irrigation development as part of a wider transformation of the fluvial landscape rather than simply as a history of canal construction (Sato, 1982; Tamaki, 1984; Kanto Regional Agricultural Administration Office, 1987).

This long history is reflected in the concentration of irrigation heritage within the Tone River system. Six irrigation systems are now recognised by the International Commission on Irrigation and Drainage (ICID) as World Heritage Irrigation Structures (WHIS): the Naganoseki Irrigation Canal, Ogawazeki Irrigation Canal, Tenguwa Irrigation System, Bizenkyo Irrigation System, Kasai Irrigation System, and Minuma-Dai Irrigation System (ICID, n.d.; MAFF, 2026). Their historical settings and engineering characteristics differ considerably, ranging from long-established tributary irrigation to large regional canals and lowland water-management networks.

Historical irrigation in Japan and monsoon Asia developed through interactions among environmental conditions, accumulated engineering knowledge, agricultural production, and collective water management (Tabayashi, 1987; Hatcho et al., 2010). Studies of irrigation heritage similarly emphasise engineering knowledge, relationships with the natural environment, and the social and institutional dimensions of water management (Li et al., 2020). In the Tone River basin, individual irrigation systems have generally been documented in relation to their own historical development, while basin-scale studies have provided broader accounts of river engineering and channel transformation. Considering these perspectives together offers an opportunity to examine irrigation heritage within the historical transformation of the river basin.

This paper reviews the historical development of major irrigation systems in the Tone River basin, focusing primarily on the late sixteenth to eighteenth centuries and examining their relationships with river engineering, flood control, drainage, agricultural reclamation, and water-management institutions. The review draws on major Japanese historical syntheses, including Sato (1982), Tamaki (1984), the History of Agricultural Water Use in the Tone River System (Kanto Regional Agricultural Administration Office, 1987), and the Floods of the Tone River (Tone River Research Group, 1995), together with previous studies, English-language literature, and official ICID and Japanese government documentation. Particular attention is given to the coexistence and interconnection of irrigation systems developed in different periods. By considering these systems together, the paper interprets the irrigation heritage of the basin as a layered water-management landscape in which older and newer systems were repeatedly reorganised in relation to one another rather than simply replaced.

2. Historical transformation of the Tone River basin

Before the early modern period, the Kanto Plain contained a complex network of rivers, distributary channels, wetlands, shallow lakes, and former channels. The low-gradient alluvial plain was traversed by the Tone, Ara, Watarase, Kinu, and Kokai rivers, whose shifting channels contributed to extensive areas vulnerable to flooding and poor drainage. At the same time, these channels and depressions later provided routes and storage spaces that could be incorporated into agricultural water-management systems. Japanese historical syntheses consequently describe the development of the basin as a long process in which river-course change, flood control, irrigation, drainage, and reclamation progressively transformed the lowland landscape (Sato, 1982; Tamaki, 1984; Kanto Regional Agricultural Administration Office, 1987).

A major phase of deliberate river reorganisation began after Tokugawa Iyasu entered Edo in 1590. The closure of the Aino River in 1594 was one of the early interventions associated with the subsequent reconfiguration of the Tone River system. During the following decades, successive works changed the connections among the Tone, Watarase, Kinu, Kokai, Ara, and lower river systems (Sato, 1982; Tamaki, 1984; Musiaki, 1988). The process now termed the eastward diversion of the Tone River should therefore not be understood as a single engineering project with a single purpose or completion date. Musiaki (1988) identified transportation, land reclamation, military defence, and flood protection among the purposes of historical river works. Trošelj and Hanasaki (2025) further showed through hydrological modelling that the altered connections improved low-flow conditions along routes important for inland navigation.

The engineering practices associated with the Ina family are often described collectively as the Kanto method (Kanto-ryu or Ina-ryu). This approach made substantial use of existing river forms and floodplain topography. In flood control, meandering channels, discontinuous levees, flood-retention areas, and overflow spaces could be retained; in agricultural water management, existing streams and former channels were incorporated into irrigation and drainage networks (Sato, 1982; Tamaki, 1984; Kimura, 2017). Low-lying channels and impoundments could store diverted water while also collecting drainage from upstream areas (Sato, 1982; Kimura, 2017). This should be understood as a general historical characterisation rather than as a uniform technical standard, but it helps explain why irrigation and drainage were frequently intertwined in the early-modern lowlands. The same general distinction between these earlier arrangements and later direct-river diversion is also evident in the historical agricultural-water literature (Kanto Regional Agricultural Administration Office, 1987, n.d.-a).

By the early eighteenth century, a different approach to river and agricultural development became increasingly important in major reclamation projects under Tokugawa Yoshimune, particularly through the work of Izawa Yasobē Tamenaga. The approach generally characterised as the Kishu method (Kishu-ryu) placed greater emphasis on fixed river channels, more continuous embankments, direct diversion from large rivers, and clearer separation of irrigation and drainage (Kimura, 2017; Kanto Regional Agricultural Administration Office, 1987). The Minuma-Dai Irrigation System, completed in 1728, is a representative example: a long-distance canal conveyed water from the Tone River, replacing the former Minuma reservoir as an irrigation source and enabling reclamation of the reservoir area (Kanto Regional Agricultural Administration Office, 1987; ICID, n.d.).

The contrast between the Kanto and Kishu methods is useful for describing changes in engineering practice, but it should not be interpreted as a simple technological replacement. Earlier channels, storage functions, and drainage-reuse networks remained in use after newer works were constructed. In some cases, later systems became physically connected with earlier ones. The historical transformation of the Tone River basin is therefore better understood as a process of cumulative reorganisation in which successive hydraulic approaches were superimposed upon existing landscapes and water-management systems.

3. Development of major irrigation systems

The irrigation history of the Tone River basin cannot be represented by a simple sequence of canal construction. The History of Agricultural Water Use in the Tone River System (Kanto Regional Agricultural Administration Office, 1987) treats major irrigation development through a series of individual canals, tributary networks, regional systems, and reclamation projects. These units differ substantially in scale and character. Table I therefore presents six WHIS-recognised systems together with selected additional examples that illustrate different historical settings and approaches to water management.

Table I. selected major historical irrigation and water-management systems in the Tone River basin

Irrigation or water-management system	Major development period	Main water source	Historical and hydraulic characteristics	WHIS recognition year
Naganoseki Irrigation Canal	Before 1645; traditional origin much earlier	Karasu River	Long-established tributary irrigation adapted to local conditions	2016
Ogawazeki Irrigation Canal	Exact date unknown; over 400 years old	Ogawa River	Traditional tributary irrigation adapted to local topography	2014
Yaba Weir and Kyūhaku Canal	Late 16th–early 17th century	Watarase River	Regional Watarase irrigation developed around the transition to the Tokugawa period	—
Tenguwa Irrigation System	1601–1610; original canal completed in 1604	Tone River	Early-Tokugawa diversion adapted to variable river stages; later expanded	2020
Bizenkyo Irrigation System	1604	Tone River	Excavated canal combined with existing channels and storage functions	2020
Oka Weir Irrigation System	approximately 1630	Kokai River	Early diversion system in the Kokai River region	—
Kasai Irrigation System	Late 16th century–1719; successive development	Tone River system and former channels	Lowland network of former channels and tame-i integrating irrigation, drainage, and water reuse	2026
Okatō Irrigation System	1664–1672; later reactivated	Watarase River	Early alluvial-fan canal development constrained by difficult and limited water intake	—
Hanyūryō Irrigation System	Early 17th century onward; repeatedly reorganised	Changing sources within the Tone River system	Changing water sources and inter-system connections	—
Yoshida and Ezure Irrigation Systems	1725–1726	Kinu River	Kyōhō-period irrigation linked to reclamation and water-source reorganisation	—
Iinuma Reclamation and Irrigation–Drainage System	From 1725	Kinu River (planned irrigation supply)	Reclamation linking Tone River drainage with planned Kinu River irrigation	—
Minuma-Dai Irrigation System	1728	Tone River	Long-distance diversion enabling reclamation and irrigation–drainage separation; return flow reused downstream	2019
Note: WHIS-recognised systems are shown in bold, with the year of WHIS recognition given in the final column; — indicates non-WHIS contextual examples. Dates indicate documented construction dates or major periods of development and do not necessarily represent the initial origin of the entire water-management system. English names of non-WHIS systems are descriptive translations used in this paper.				

3.1 Early and early-modern irrigation development

Irrigation in the Tone River system predates the large-scale river works of the Tokugawa period. The Naganoseki Irrigation Canal is traditionally considered to have origins approximately one thousand years ago, although its initial construction date is uncertain; ICID conservatively records it as having

been built before 1645, when its existence is clearly documented. The Ogawazeki Irrigation Canal likewise has no securely established construction year but is estimated to be more than four centuries old. These systems show that locally adapted irrigation had already developed in tributary environments before the large regional projects of the seventeenth century (ICID, n.d.).

Late-sixteenth- and early-seventeenth-century developments in the Watarase River area, including the Kyūhaku Canal and Yaba Weir, further demonstrate that substantial regional irrigation was developing around the transition to the Tokugawa period (Kanto Regional Agricultural Administration Office, 1987). Around the beginning of the seventeenth century, irrigation development expanded markedly in scale. The Tenguwa Irrigation System was planned in 1601 and its original canal completed in 1604. Subsequent extensions enlarged the network through the following years. The system was adapted to the variable hydraulic conditions of the Tone River, and historical intake arrangements were designed to maintain diversion under changing river stages. The Bizenkyo Irrigation System was likewise constructed in 1604 under Ina Tadatsugu. Its development combined newly excavated canals with existing watercourses and storage functions, and its downstream flows contributed to neighbouring irrigation areas. These systems illustrate how early-Tokugawa canal development combined newly constructed infrastructure with the existing river landscape (Kanto Regional Agricultural Administration Office, 1987; ICID, n.d.).

3.2 Expansion and interconnection of lowland irrigation networks

The Kasai Irrigation System provides a contrasting example of cumulative lowland development. It cannot appropriately be assigned a single construction year because the network developed through successive stages from the late sixteenth century to 1719. Former river channels were progressively incorporated as conveyance and storage routes, and tame-i were used to maintain water levels in the extremely flat lowlands. These facilities could collect both diverted river water and drainage from upstream agricultural land, allowing water to be reused farther downstream (Sato, 1982; Tamaki, 1984; Kanto Regional Agricultural Administration Office, 1987; Kimura, 2017).

This repeated use was a fundamental characteristic of the Kasai system (Kimura, 2017). The distinction between irrigation and drainage was therefore less clear than in later systems based on separated canals: drainage from one area could constitute part of the irrigation supply for another. The historical significance of Kasai lies not simply in the age of individual canals but in the gradual connection of former channels, storage functions, drainage routes, and later diversions from the Tone River.

Other areas of the basin developed through different combinations of local works and regional reorganisation. Along the Watarase River, systems such as Okatō were developed during the seventeenth century, while the Kinu and Kokai river regions contained multiple weirs and canal systems rather than single unified facilities. Hanyūryō further demonstrates that the boundaries and water sources of historical irrigation systems were not fixed. Its relationship with neighbouring systems changed as new canals were constructed and regional water allocation was reorganised (Kanto Regional Agricultural Administration Office, 1987).

3.3 Kyōhō-period reorganisation

The early eighteenth century brought an important phase of projects combining irrigation, drainage, and reclamation. The linuma reclamation initiated in 1725 is a useful example. The scheme involved drainage of the wetland towards the Tone River together with a planned new irrigation supply from the Kinu River. The intended irrigation supply did not fully perform as planned, but the project nevertheless demonstrates an integrated concept in which water supply, drainage, and land reclamation were considered together (Kanto Regional Agricultural Administration Office, 1987, n.d.-b).

The Minuma-Dai Irrigation System provides a clearer example of large-scale reorganisation. The former Minuma reservoir had supplied irrigation to downstream agricultural land, so its reclamation required a replacement source. In 1728, a new canal was completed to convey water over a long distance from the Tone River. The project combined direct large-river diversion, long-distance conveyance,

reclamation of the former reservoir, and clearer spatial separation between irrigation and drainage (Kanto Regional Agricultural Administration Office, 1987; ICID, n.d.). However, the new system did not eliminate the older lowland network. Return flow and surplus water from the Minuma-Dai area entered downstream former channels and contributed to the water supply of the Kasai system (Sato, 1982; Tamaki, 1984; Kanto Regional Agricultural Administration Office, 1987; Kimura, 2017). A newer irrigation system characterised by direct diversion and irrigation–drainage separation therefore became hydrologically connected with an older network based on former channels, storage, and repeated water use.

Taken together, these examples show that early-modern irrigation development in the Tone River basin was neither uniform nor linear. Long-established tributary irrigation, large early-Tokugawa canals, lowland reuse networks, and Kyōhō-period regional reorganisation coexisted and interacted. The six WHIS-recognised systems represent different historical settings and approaches to irrigation development within this broader transformation of the Tone River basin.

4. Irrigation, flood control, drainage, and water governance

The development of irrigation in the Tone River basin was inseparable from drainage and flood management, particularly in the low-gradient plains south of the main river. Former channels and low-lying watercourses could serve as irrigation sources, drainage routes, or temporary storage spaces according to local hydraulic conditions (Sato, 1982; Tamaki, 1984; Kimura, 2017). Major floods also continued to affect the basin after the seventeenth-century river works, requiring continuing adaptation of local flood-protection arrangements (Tone River Research Group, 1995).

The reuse of drainage water illustrates this interdependence particularly well. In the Kasai system, drainage collected in lower channels could become a downstream water source. Although the Minuma-Dai system introduced clearer separation between irrigation and drainage, return flow from the new system was subsequently reused within the older Kasai network. Consequently, technological change did not result in complete functional separation at the basin scale (Sato, 1982; Tamaki, 1984; Kanto Regional Agricultural Administration Office, 1987; Kimura, 2017).

Physical interdependence was accompanied by territorial forms of collective water management. In the Saitama Plain, groups of villages were historically organised into regional units known as *ryō*. Nakamura (2017) emphasised that *ryō* were not uniform administrative divisions; their origins and functions varied. In the lowlands of the Tone and Ara rivers, however, villages within a *ryō* often shared interests in flood protection, drainage, and irrigation. Cooperation therefore developed around levee maintenance and shared hydraulic facilities (Nakamura, 2017).

Such arrangements did not imply harmonious management. The same hydraulic connections could create conflict between neighbouring territories. Levees protecting one area could increase or prolong inundation elsewhere, and some such boundary levees were known as *ronjo-tei*, or “disputed levees”; the *Chūjō-tei* provides a prominent example of upstream–downstream conflict over flood protection (Nakamura, 2017). Nakamura’s account therefore shows that hydraulic interdependence was associated with both cooperation within territories and conflict across them.

The historical significance of *ryō* lies in this relationship between hydraulic and institutional geography. River engineering altered the pathways of water, irrigation and drainage networks redistributed water and risk, and communities developed arrangements for cooperation and negotiation around the resulting benefits and burdens. Water-management institutions thus formed part of the historical landscape within which the Tone River irrigation systems developed.

5. Heritage value of irrigation systems in the Tone River basin

The six WHIS-recognised systems differ considerably in origin, scale, geomorphic setting, and engineering form. Naganoseki and Ogawazeki represent long-established local irrigation adapted to tributary environments. Tenguwa and Bizenkyo illustrate large early-Tokugawa canal development.

Kasai represents a cumulatively formed lowland network based on former channels, storage, irrigation–drainage interaction, and repeated use, whereas Minuma-Dai represents the later development of long-distance diversion, clearer irrigation–drainage separation, and reclamation.

At the level of individual structures, their heritage value lies in long histories, engineering ingenuity, adaptation to local environmental conditions, and continuing relationships with agricultural landscapes. These characteristics are consistent with broader studies that emphasise engineering knowledge, long-term adaptation to environmental conditions, and the social and institutional dimensions of irrigation management (Hatcho et al., 2010; Li et al., 2020).

The historical evidence reviewed here suggests an additional, basin-scale perspective. The systems developed within changing relationships among rivers, former channels, flood-control works, drainage routes, reclaimed land, and existing irrigation networks. In some cases, later infrastructure directly affected older systems. The Minuma-Dai–Kasai relationship is the clearest example, while the changing connections of Bizenkyo and Hanyūryō provide another indication that irrigation systems cannot always be understood as hydraulically isolated units (Sato, 1982; Tamaki, 1984; Kanto Regional Agricultural Administration Office, 1987; ICID, n.d.).

The heritage significance of the Tone River irrigation systems can therefore be considered at two complementary scales: the individual WHIS and the wider historical water-management landscape. At the basin scale, the six WHIS collectively illustrate a range of historical approaches to agricultural water management under different geomorphic and hydraulic conditions within the Tone River system.

This paper consequently proposes that the irrigation heritage of the Tone River basin should be viewed not simply as a collection of isolated historical structures, but as the result of a layered historical process in which river engineering, irrigation, drainage, reclamation, agricultural development, and collective water management developed and were repeatedly reorganised in relation to one another. “Layered” is used here as an analytical interpretation rather than as an official heritage category. It emphasises that later systems did not necessarily erase earlier ones and that historical relationships among systems provide an important context for understanding their heritage value.

6. Conclusion

The historical development of irrigation in the Tone River basin was closely linked with the transformation of the Kanto Plain. From the late sixteenth century onward, river-course modification, flood control, irrigation development, drainage improvement, and reclamation interacted to create new conditions for agricultural production.

Although the contrast between the Kanto and Kishu methods is useful for describing changes in engineering practice, the history of the basin was not a simple replacement of old systems by new ones. Existing channels, storage functions, drainage routes, and water-use practices continued to operate and sometimes became connected with newer infrastructure. The Minuma-Dai–Kasai relationship provides a clear example of this cumulative reorganisation.

The six World Heritage Irrigation Structures in the Tone River system represent different historical settings and expressions of agricultural water management within this broader transformation. Their significance lies both in their individual historical and engineering characteristics and in their wider relationships within a changing basin-scale water-management landscape. This perspective provides a basis for interpreting the Tone River irrigation heritage as the product of a layered interaction among rivers, agricultural landscapes, engineering practices, and collective water management.

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CHARACTERISTICS AND VALUES OF ANCIENT WEIRS IN CHINA

CARACTÉRISTIQUES ET VALEURS DES ANCIENS SEUILS EN CHINE

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ABSTRACT

Among China's 42 World Heritage Irrigation Structures, 18 are weir-dominated projects. Ancient weir projects differ significantly from modern barrages and dams. Most are arranged in a curved pattern or obliquely to the river, intentionally extending the weir axis length. While this may seem to consume more labor and construction materials, such layout increases the overflow section and capacity of the weir, effectively reducing the water level above the weir, and simultaneously disperses and transmits the water flow shear force that causes dam failure to the river embankments. Some ancient weirs also utilize naturally formed step-pool systems in rivers to construct weirs on pools, leveraging the energy dissipation effect of deep pools to reduce the impact of floods on the weirs. These construction methods of ancient weir projects can effectively mitigate the impact of floods, enhance engineering resilience, and extend the project life cycle. This not only embodies the wisdom of the ancients but also demonstrates the concept of respecting nature and the unity of man and nature, which is a historical practice of the contemporary "river ethics" concept. From the perspective of modern engineering technology, these practices have scientific theoretical basis and have been widely applied, such as long-axis weirs like "curved weirs" and "duckbill weirs", and the use of artificial step-pool systems for mountain river regulation. In-depth research on these ancient water conservancy projects with multidisciplinary participation to excavate the wisdom of the ancients can not only provide reference for the construction and management of contemporary water conservancy projects but also play an important role in enhancing national cultural confidence.

RÉSUMÉ

Parmi les 42 structures d'irrigation inscrites au patrimoine mondial en Chine, 18 sont des projets dominés par des barrages en seuil. Les projets de seuils anciens diffèrent considérablement des barrages et des seuils modernes. La plupart sont disposés selon une configuration courbe ou oblique par rapport au cours d'eau, prolongeant intentionnellement la longueur de l'axe du seuil. Bien que cela puisse sembler consommer plus de main-d'œuvre et de matériaux de construction, une telle disposition augmente la section et la capacité de déversement du seuil, réduisant ainsi efficacement le niveau d'eau en amont, tout en dispersant et en transmettant simultanément la force de cisaillement de l'écoulement de l'eau vers les digues de la rivière.

Certains anciens seuils exploitent également les systèmes naturels à gradins et mares formés dans les rivières pour construire des seuils sur ces mares, tirant parti de l'effet de dissipation d'énergie des bassins profonds pour réduire l'impact des crues sur les ouvrages. Ces méthodes de construction permettent d'atténuer efficacement l'impact des inondations, de renforcer la résilience des ouvrages et de prolonger leur cycle de vie. Cela incarne non seulement la sagesse des anciens, mais démontre également le concept de respect de la nature et d'unité entre l'homme et la nature, constituant une pratique historique de la notion contemporaine d'« éthique des fleuves ».

Du point de vue de la technologie de l'ingénierie moderne, ces pratiques reposent sur des bases théoriques scientifiques et ont été largement appliquées, comme les seuils à axe long (tels que les « seuils courbes » et les « seuils en forme de bec de canard »), ainsi que l'utilisation de systèmes artificiels à gradins et mares pour l'aménagement des rivières de montagne. Des recherches approfondies,

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impliquant une approche pluridisciplinaire sur ces anciens projets d'hydraulique pour mettre au jour la sagesse des anciens, peuvent non seulement servir de référence pour la construction et la gestion des projets hydrauliques contemporains, mais aussi jouer un rôle important dans le renforcement de la confiance culturelle nationale.

Keywords: World Heritage Irrigation Structures; ancient weirs; oblique layout; step-pool system; cultural confidence

1. Introduction

Irrigation heritage projects have withstood hundreds or even thousands of years of climate change and natural vicissitudes and are still inherited and used today, which fully proves their scientificity and rationality in planning, design, construction and management. The construction of these irrigation projects cannot be accomplished overnight. From the initial conception to the final realization of their due benefits, they often require countless attempts, revisions and improvements. With the in-depth understanding of natural laws and the continuous emergence of new construction materials, these projects have undergone multiple transformations and adjustments in the long river of history, thus accumulating rich scientific experience. These experiences still have important guiding significance for the construction and management of modern water conservancy projects. For example, the fish mouth project of Dujiangyan underwent multiple adjustments in position and materials during the Qing Dynasty, and it was not until the modern adoption of concrete materials that a permanent project was finally formed. The Zhengguo Canal, due to the downcutting of the Jing River, has led to the continuous upward movement of the water intake, leaving numerous relics of ancient water diversion inlets. When Mulan Weir was first constructed, it was destroyed repeatedly by floods and tidal surges. It was not until the weir was built at the location with the least impact from floods and tides that it has been in continuous use to this day. These irrigation heritage projects demonstrated excellent environmental adaptability and low-impact development characteristics in historical periods. On the one hand, this was limited by the scientific and technological level and construction materials at that time; on the other hand, it also reflected the ancient Chinese philosophical thought of following natural laws and pursuing the unity of man and nature.

China is a country with a vast territory and diverse landforms, which has nurtured distinctive irrigation projects. At present, China has 42 World Heritage Irrigation Structures, covering almost all types of irrigation projects, making it the country with the richest variety, the widest distribution and the most significant benefits. Among these projects, 18 are dominated by weirs, which is the largest number among all project types. World Heritage Irrigation Structures is an emerging academic field. At present, most scholars conduct research on the historical and cultural value of heritage projects, while few conduct in-depth research from the perspective of water conservancy science and technology. Based on the understanding and research of China's World Heritage Irrigation Structures in work, the authors introduce the engineering characteristics of weir-type projects in China's World Heritage Irrigation Structures and analyze their engineering scientific and technological value and connotation.

2. Characteristics and Value Analysis of Ancient Weir and Dam Projects

As a type of river-blocking water diversion irrigation project, weirs have wide applicability in mountainous and hilly areas. In Sichuan, Hunan, Jiangxi, Zhejiang, Anhui, Fujian and other places in China, a large number of weir projects have been built since ancient times. The landforms in these areas are different, so the ancients built distinctive weirs according to local conditions.

For example, in the Sichuan Basin, due to the relatively flat terrain, the ancients built many large-scale weirs such as the Tongji Weir in Sichuan to meet the irrigation needs of large areas of farmland. In the hilly areas of Zhejiang and Jiangxi, the ancients used the terrain elevation difference to build many stepped weirs to achieve efficient water diversion irrigation. The weir projects built along the coast of Fujian have the function of storing fresh water and repelling salt water, so the site selection is very important considering the dual impact of floods and tides. In short, China's weir projects are adapted to

local conditions and have their own characteristics, fully demonstrating the wisdom and creativity of the ancients in water conservancy engineering construction.

2.1 Oblique Layout of Weirs and Dams with River Channels

Most ancient weirs adopt an oblique layout with the river in planning and arrangement. For example, in the Tianbao Weir in Fuqing, the builders intentionally lengthened the dam axis, and the weir is arranged obliquely with a length of 216m. If designed as an orthogonal straight weir, about 90m would be sufficient to intercept the water surface, as shown in Figure 1.



Figure 1. Schematic diagram of Tianbao Weir project layout

From an intuitive analysis, the oblique angle between the weir crest axis and the flow direction leads to an increase in the overflow front length. Under specific flow conditions, the water head decreases accordingly; or under a fixed water head, the discharge over the weir increases. The actual length of the weir body is the key factor determining its flow capacity—the longer the actual length, the stronger the flow capacity. The design of the oblique weir with a long dam axis not only ensures the water conveyance efficiency of the main canal downstream but also reduces the adverse impact on the flood discharge capacity of the weir during flood seasons.

A series of model test data reveal that there is a special hydraulic phenomenon in oblique weirs—the "self-submergence phenomenon"[1]. Specifically, the water flow discharged from the overflow weir collides with the river bank, causing the water surface to rise and form a fish-back-like water surface shape. Due to the interaction of the discharged flow streamlines, local submerged flow may occur in the part of the weir section near the bank. To solve this problem, Tianbao Weir designed a funnel-shaped structure on the right bank, and the right bank water intake is exactly located at the tip of the funnel. This design can not only regulate the river flow, ensure smooth water intake at the water intake during the dry season and transport it to the irrigation area through the main canal, but also largely eliminate the "self-submergence phenomenon".

Further analysis shows that when the water flow impacts the obliquely arranged weir parallel to the river channel, the water flow shear force decreases with the increase of the weir inclination angle. If the weir is inclined to be parallel to the river channel, theoretically the shear force of the water flow on the weir will approach zero, thus greatly enhancing the weir's ability to resist floods. This is also the theoretical basis for the adoption of the fish mouth diversion dike non-dam water diversion form in large rivers.

2.2 Weir Construction in Wide River Sections

Different from the modern practice of building dams in narrow canyon areas, ancient weir construction usually chose wide river sections. In these places, the ancients sometimes used naturally formed sandbars or bedrock in the riverbed to connect two sections of the river-blocking weir. For example, the Jiang-Xi Weir project in Longyou is located in the wide area after the river flows out of the mountains, and skillfully uses natural sandbars to construct two weirs, Jiang Weir and Xi Weir, as shown in Figure 2; the Wushitan Weir in the Liaohe Irrigation District also builds the dam at the position where the river channel suddenly widens, and uses bedrock boulders above the water surface in the river channel as supports to divide the weir body into two sections to enhance its stability. From these examples, it can be inferred that the ancients had a certain degree of scientific understanding of river dynamics. They recognized that in wide river sections, the flow velocity will be significantly reduced, and by connecting sandbars and bedrock, the weir is divided into multiple parts, thereby improving its torsional strength. In addition, as can be seen from the diagram of Jiang-Xi Weir, Jiang Weir, sandbar and Xi Weir can all overflow and discharge flood during flood periods, which greatly reduces the obstruction of the project to floods, and correspondingly, the impact of floods on the project is also reduced, reflecting the simple concept of harmonious coexistence between man and nature of the ancients. They not only demonstrated wisdom in technology but also embodied respect and compliance with nature in philosophy. This practice not only effectively utilized natural conditions but also reduced damage to the environment, enabling weir projects to better integrate with the surrounding natural environment. In this way, the ancients not only realized the function of water conservancy projects but also protected the ecological environment, demonstrating their profound understanding and respect for natural laws.



Figure 2. Aerial view of Jiang-Xi Weir

2.3 Utilization of Bend Circulation for Sediment Flushing

Ancient weir projects are usually located at the curved parts of rivers, with water intakes set on the concave banks of the rivers. For example, the Tianbao Weir mentioned above and the Chatan Weir shown in the figure have their water diversion inlets located on the concave banks. This layout enables the weir to use the inertial trend of natural water flow to guide the water smoothly into the irrigation

channel. According to the theory of bend circulation in hydraulics, when the water flow enters a bend, under the action of centrifugal force, the surface water flow will move towards the concave bank of the river, while the bottom water flow will move towards the convex bank, thus forming a closed circulation, which is usually called bend circulation. When bend circulation meets longitudinal water flow, a spiral flow is generated[2]. This flow pattern ensures that the water intake on the concave bank can draw more surface clear water and reduce sediment deposition in the water intake and channels. The main dam and auxiliary dam of Chatan Weir are connected by a sandbar and built at a large-angle turn of the river, guiding the mid-channel part of the water flow into the channel smoothly, while the excess water overflows laterally to reduce the direct impact on the weir, as shown in Figure 3. During flood seasons, Chatan Weir functions similarly to the "Feisha Weir" of Dujiangyan. Through the bend circulation movement, most of the sediment is effectively discharged into the downstream river channel, thereby reducing the siltation of the channels and ensuring the long-term stable operation of the irrigation system.



Figure 3. Aerial view of Chatan Weir

2.4 Weir Construction on Pools

The riverbeds of steep mountain rivers are often composed of alternating steep sections, gentle sections and deep pools, presenting a series of stepped shapes, which is called the step-pool system, as shown in Figure 4. The typical morphological characteristics of step-pool rivers are reflected in the large undulations of the longitudinal profile of the bed surface with a series of inflection points. Along the river, the water flow alternates between rapid flow and slow flow, and there are also many inflection points on the water surface line, presenting an obvious continuous stepped shape. Through slow and continuous erosion and downcutting, the river makes the riverbed have a curved characteristic in the longitudinal direction. The sediment particles at the steps in the riverbed are relatively coarse, with large pebbles and even boulders, while the sediment particles in the deep pools downstream of the steps are finer than those at the steps, and very fine sand can also exist[3]. As early as 1957, Leopold and Wolman noticed this river geomorphic feature, but the term did not appear until the 1980s. Judd called this landform "steps" in 1964, and it was not until 1982 that Whittaker and Jaeggi, and in 1985 Petts and Foster, all called it the "Step-Pool system", after which this term was widely accepted[4]. The existence

of deep pools has a significant hydraulic energy dissipation effect, which can effectively slow down the scouring force of water flow on the riverbed, thus keeping the basic area of the riverbed relatively stable, which is also an important manifestation of river maturity. At present, the use of artificially constructed step-pool systems for mountain river regulation has been widely applied.

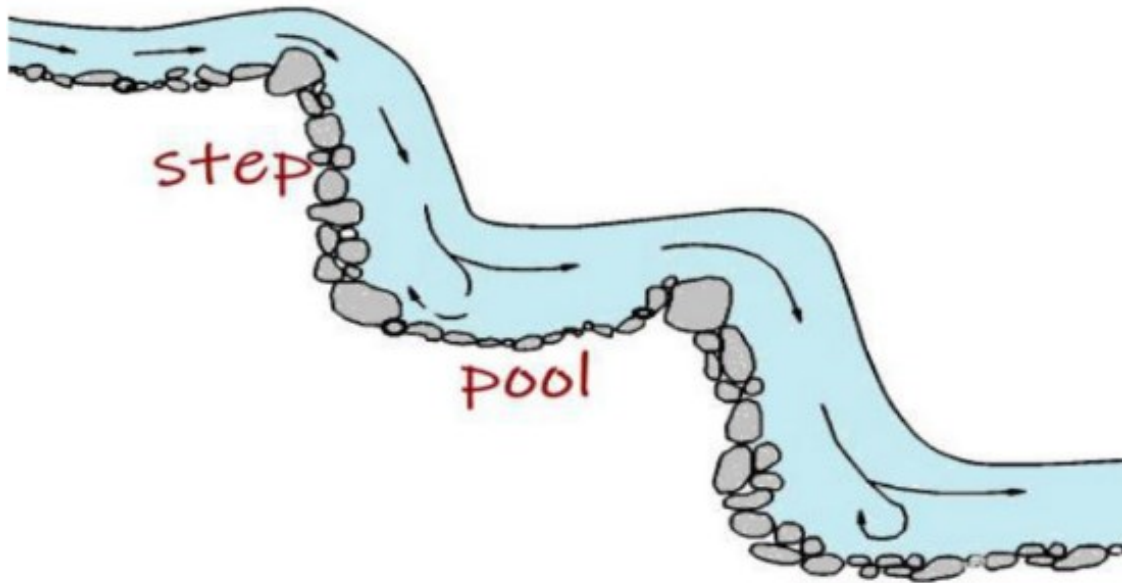


Figure 4. Schematic diagram of step-pool system

However, the utilization of this river landform did not begin with the research of modern scholars. As early as thousands of years ago in ancient China, our ancestors had conducted in-depth observations and ingenious utilization of this river landform. In 27 AD, Lu Wentai led people to build weirs on pools and dig canals to divert water for irrigation on the Baisha River, successively building 36 weirs, which is not just a simple cascade development model [5]. When constructing these weirs, the ancients skillfully utilized the characteristics of step-pool systems, and most weirs were built at the lower edges of deep pools. These deep pools can effectively use their energy dissipation effect, summarizing the water control method of "deeply dredge the pools, lowly build the weirs", reducing the impact of water flow on the weirs, thereby extending the service life of the weirs and improving their water storage capacity. This ancient and wise utilization method demonstrates the ancients' profound understanding of natural laws [6].

2.5 Application of Traditional Construction Materials

In ancient times, the construction of weir projects mainly relied on earth and wood materials. Due to their vulnerability, these materials were often attacked and destroyed by floods, so large-scale repairs were required almost every year. With the evolution of history, by the Song Dynasty, with the rise of large-scale stone structures such as seawalls and the significant progress of engineering technology, masonry technology began to be gradually applied to the construction and maintenance of weir projects. At the same time, the traditional Chinese wooden mortise and tenon structure technology was also skillfully integrated into masonry technology, which not only reflected the significant improvement of engineering construction technology but also marked technological innovation.

For example, in the Northern Song Dynasty, people built Mulan Weir, a large-scale and exquisitely designed stone river-blocking weir for storing fresh water and repelling salt water. The construction of this weir project fully demonstrated the high level of masonry technology at that time, and its "general pillars" are repeatedly cited in literature as a symbol of technological achievement. In the Tang Dynasty, the Tuoshan Weir project was originally constructed with an earth-wood structure, and in the Song Dynasty, it was reconstructed with a masonry structure. After reconstruction, each stone slab of Tuoshan Weir weighed several tons. To further enhance the stability of the dam body, craftsmen also drilled holes in the stone slabs and poured molten iron into them, making these huge stones tightly connected together. In addition, records of Tianbao Weir show that in the Song Dynasty, people had already used molten iron to reinforce the dam foundation, which further proves the advancement and innovation of engineering technology at that time. Overall, the upgrading of construction materials is the development trend of ancient weir projects, and the progress of modern dam technology is also an important manifestation of this trend.

3 Conclusion

Irrigation heritage projects that have been inherited for thousands of years have withstood severe tests of various climate changes, demonstrated extremely high engineering resilience and adaptability, and have been proven to be models of sustainable operation. The reasons are nothing more than two aspects: first, the planning and design of these projects are scientific and conform to natural laws; second, the operation and management systems of the projects are in line with the historical trend. In agricultural society, irrigation projects were not only simple irrigation projects but also social water conservancy projects, bearing the profound development of society, economy, science and technology, and culture. Therefore, when we study and excavate the value of these irrigation projects today, we need more experts and scholars from different disciplines to participate and interpret the profound connotations contained in these precious historical projects from different perspectives.

The wisdom of these irrigation projects is not only a treasure in the water conservancy field but also a crystallization of the wisdom and creativity of the Chinese nation. With their unique design concepts and exquisite construction techniques, these ancient water conservancy projects not only solved practical problems such as agricultural irrigation and flood control and drainage at that time but also left valuable experience and enlightenment for future generations. In modern society, with the rapid development of science and technology and the increasingly prominent environmental problems, the wisdom of ancient weir projects is once again shining with new light. The sustainable development concepts contained in these ancient projects, such as water-saving irrigation and ecological restoration, provide valuable ideas for us to meet the challenges of water shortage and environmental degradation.

In the planning and construction of water conservancy projects, we can learn from the ecological design concepts of ancient weir projects, pay attention to protecting the natural ecological environment, and realize the harmonious coexistence of water conservancy projects and the ecological environment. At the same time, through systematic publicity and display of the wisdom and concepts contained in these projects, letting the public understand the intelligence of our ancestors has important practical significance for enhancing national cultural confidence and cultivating the consciousness of heritage protection. These projects not only demonstrated the wisdom of the ancient people in technology but also reflected the profound heritage of the Chinese nation in culture. They are not only witnesses of history but also models of the combination of modern science and technology and traditional wisdom, which are worthy of in-depth research and inheritance.

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TRADITIONAL MEADOW IRRIGATION IN EUROPE

L'IRRIGATION TRADITIONNELLE DES PRAIRIES EN EUROPE

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ABSTRACT

Traditional irrigation in Central Europe differs significantly from that in other regions of the world: rather than arable land, it was primarily meadows that were irrigated in order to achieve higher hay yields and thereby provide for more livestock over the winter. Until the introduction of artificial fertilisers after the Second World War, livestock manure was the key basis of soil fertility. Particularly on the nutrient-poor, sandy soils of northern Germany, the combination of nutrient enrichment and regular moistening was crucial, as water seeps away quickly there.

Building on natural flooding, various forms of meadow irrigation developed: 'wild irrigation', slope irrigation and, finally, the labour-intensive ridge system. In the Lüneburg Heath, this gave rise to the Suderburg ridge system, featuring artificially constructed ridges 7–12 metres wide and up to 0.4 metres high, whose channels had to be meticulously maintained. In addition to a limited fertilising effect, key benefits included frost protection, drainage of waterlogged areas, the promotion of valuable grasses and pest control.

With the advent of artificial fertilisers, meadow cultivation lost its significance; most of these systems disappeared. Traditional gravity irrigation, which relied heavily on communal organisation, was recognised as an intangible UNESCO World Heritage site in 2023. In north-eastern Lower Saxony, a few remnants of the irrigation ridges are still visible – yet at the same time, the region is now Germany's most intensively irrigated arable farming region, which underlines the former importance of meadow irrigation.

RÉSUMÉ

L'irrigation traditionnelle en Europe centrale diffère considérablement de celle pratiquée dans d'autres régions du monde: ce ne sont pas tant les terres arables que les prairies qui étaient irriguées, dans le but d'obtenir des rendements de foin plus élevés et, par là même, de subvenir aux besoins d'un plus grand nombre d'animaux pendant l'hiver. Jusqu'à l'introduction des engrais chimiques après la Seconde Guerre mondiale, le fumier animal constituait la principale source de fertilité des sols. En particulier sur les sols sableux et pauvres en nutriments du nord de l'Allemagne, la combinaison d'un apport en nutriments et d'un arrosage régulier était cruciale, car l'eau s'y infiltre rapidement.

S'appuyant sur les inondations naturelles, diverses formes d'irrigation des prairies se sont développées: l'irrigation sauvage, l'irrigation en pente et, enfin, le système de buttes, très exigeant en main-d'œuvre. Dans la lande de Lünebourg, cela a donné naissance au système de buttes de Suderburg, caractérisé par des buttes construites artificiellement de 7 à 12 mètres de large et pouvant atteindre 0,4 mètre de haut, dont les canaux devaient être entretenus avec le plus grand soin. Outre un effet fertilisant limité, les principaux avantages comprenaient la protection contre le gel, le drainage des zones gorgées d'eau, la promotion de graminées de grande valeur et la lutte contre les ravageurs.

Avec l'avènement des engrais artificiels, la culture des prairies a perdu de son importance; la plupart de ces systèmes ont disparu. L'irrigation traditionnelle par gravité, qui reposait largement sur une

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organisation communautaire, a été inscrite au patrimoine mondial immatériel de l'UNESCO en 2023. Dans le nord-est de la Basse-Saxe, quelques vestiges des buttes d'irrigation sont encore visibles – pourtant, cette région est aujourd'hui la zone agricole la plus intensivement irriguée d'Allemagne, ce qui souligne l'importance qu'avait autrefois l'irrigation des prairies.

Keywords: Meadow irrigation, water management, Suderburg, History

1. Introduction

Traditional irrigation in Central Europe differs in many respects from traditional irrigation in other parts of the world. In Central Europe, it was not primarily arable land that was irrigated, but meadows. In most regions, it was not water that was the limiting resource, but soil fertility. Until the widespread introduction of artificial fertilisers in agriculture after the Second World War, animal manure was practically the only way to fertilise arable land in order to maintain soil fertility. Particularly on nutrient-poor soils, the concentration of nutrients was an important prerequisite for adequate yields. In regions with low rainfall or sandy soils, regular irrigation also played an important role in grass yields. In sandy regions, the soil cannot retain rainfall sufficiently; instead, it seeps too quickly into deeper layers where plant roots cannot reach the water.

The amount of manure produced depended crucially on how many animals (particularly sheep, cows and cattle) could be kept in the barn over the winter. Manure could be collected particularly effectively in the barn, ready to be spread on the fields in the spring. The amount of hay harvested determined how many animals could be fed. Animals for which there was insufficient winter fodder were slaughtered in the autumn. For these reasons, meadow irrigation was originally widespread in Central Europe. Even today, the technique of meadow irrigation is still practised in some parts of Europe, but most of these areas have disappeared following the widespread introduction and use of artificial fertilisers in agriculture. Although some active irrigation areas are no longer used for grass production today, they are still utilised for nature conservation or groundwater recharge. Figure 1 shows an extract from a map of Germany from the late 1930s illustrating the distribution of the various forms of meadow irrigation.

In December 2023, this form of traditional irrigation in Europe was inscribed on the UNESCO List of Intangible Cultural Heritage. This article aims to present some aspects of meadow irrigation, with a particular focus on northern Germany and meadow irrigation using the 'Rückenbau' method. This method is particularly labour-intensive but is essential in flat regions to prevent water from pooling in the meadows. Stagnant water quickly becomes oxygen-deprived, causing the grass to die; in flowing, oxygen-rich water, grass can continue to grow for up to around 14 days.



Figure 1. Irrigation in Germany in the late 1930s (detail) (Böhm, 1990)

2. Forms of meadow irrigation

Meadow construction in Europe, with its various forms and the associated advantages and disadvantages, has been described in detail in a two-volume work entitled 'Traditional Irrigation – a Cultural Heritage of Europe' (Christian Leibundgut & Ingeborg Vonderstrass, 2016). The second volume also contains a detailed description of the remnants of meadow irrigation still found in Europe.

For today's observer, the question arises as to why such effort was expended on meadow construction, and in particular on the construction of irrigation ridges. All the work was carried out by hand; consequently, great importance was attached during the planning stage to constructing the ridges using earth-moving techniques to ensure a balance of earth volumes, in order to avoid major soil disturbances. Figure 2 shows the Hardau Valley near Suderburg, close to Uelzen, covered with irrigation ridges. The image depicts the experimental plots of the Meadow Construction School in Suderburg.

Figure 3 shows a map extract of this site with the corresponding irrigation ridges. This is the work of meadow construction student P. Langhans from 1909, and it illustrates how the older and wider ridges could be converted into narrower and shorter ones. The drawing also clearly shows how the ridges were integrated into the landscape. Figure 4 shows a cross-section of such a system from the same work.



Figure 2. View of the Hardau Valley in 1910; the valley floor is covered with irrigated meadows (KHG Baumgarten Collection)

Over time, various forms of meadow irrigation have developed. 'Wild irrigation' is certainly to be regarded as the oldest form, followed by slope irrigation and, finally, the construction of ridges. During floods, rivers naturally burst their banks and flood part of the valley floodplain. People have made use of this, particularly in arid regions, for example by sowing their cereals into the moist soil once the floodwaters have receded. The flooded area could be expanded in two ways. Firstly, by creating a greater backwater, for example by means of a barrier in the watercourse or, in the case of larger watercourses, by means of a weir. The second option is the construction of canals to channel the water more quickly into the area. Combining both methods is particularly effective. A further increase in the flooded area is possible through the use of devices to lift the water. In the simplest case, this is achieved by a hand-operated

Archimedes' screw, or by scoop wheels driven by the flow velocity or by animals. Today, this is done using modern pumps. These forms of flood irrigation remain the most common method of irrigation in arable farming even today. In grassland farming, slope irrigation has developed from the diversion of water via canals. On suitable terrain, for example in hilly country or low mountain ranges, water can be diverted from a watercourse via a canal. The canal is constructed with a gentler gradient than that of the watercourse itself. It is laid parallel to the slope, i.e. following the contour lines. This creates an ever-widening area between the canal and the watercourse. When the canal overflows, the water flows back into the watercourse. As the flowing water is rich in oxygen, this method can be maintained for several days without the grass's growth being adversely affected. Where the gradient is very gentle, this method can also be used in arable farming, e.g. as furrow irrigation, provided that it does not lead to soil erosion. Thanks to the soil zone permeated by the grass roots, the system is very stable and can withstand flow velocities of 1 to 2 m/s for several days, even with low bed shear stresses or shallow flow depths. As a rule, the grass continues to grow during this process. However, this does not work on flat land, as the necessary difference in elevation is lacking. In large river valleys, for example, alluvial fans formed by smaller tributaries could be irrigated via canals fed from the tributaries. It is likely that, based on observations of such systems, the technique of constructing artificial ridges was developed simultaneously in various locations during the 18th and 19th centuries. In this method, the ridges are artificially created using spades and fitted with irrigation channels along their crests. This led to the development of the so-called Suderburg ridge system in the Lüneburg Heath, as shown in Figures 2–4. The earthen channels for water distribution, and in particular the channels on the ridges, required constant maintenance and upkeep. The channels on the ridges had to be laid out exactly horizontally, and their edges had to be re-cut time and again to ensure an even distribution of water across the entire ridge. A lack of maintenance led to the formation of erosion gullies, which quickly deepened until, eventually, the meadow areas were only partially flooded. The uneven distribution of water ultimately resulted in uneven grass growth. The ridges, at least in Suderburg, were less steep than they appear in many sketches. The width was usually between 7 and 12 m, and the height of the ridges was around 0.2 to 0.4 m. Greater heights increased the risk of erosion and made construction more labour-intensive, as significantly more soil had to be moved. In order to make optimum use of the valleys and minimise soil disturbance, great care was taken in the planning of the irrigation systems.

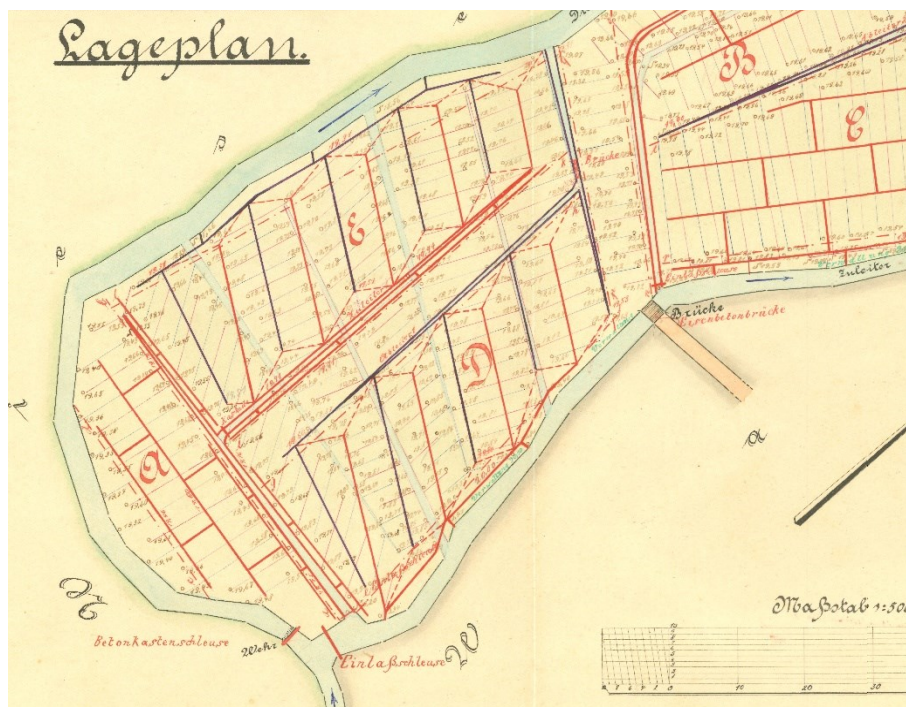


Figure 3. Extract from the site plan for the conversion of a demonstration meadow in the Hardau Valley (P. Langhans, 1909)

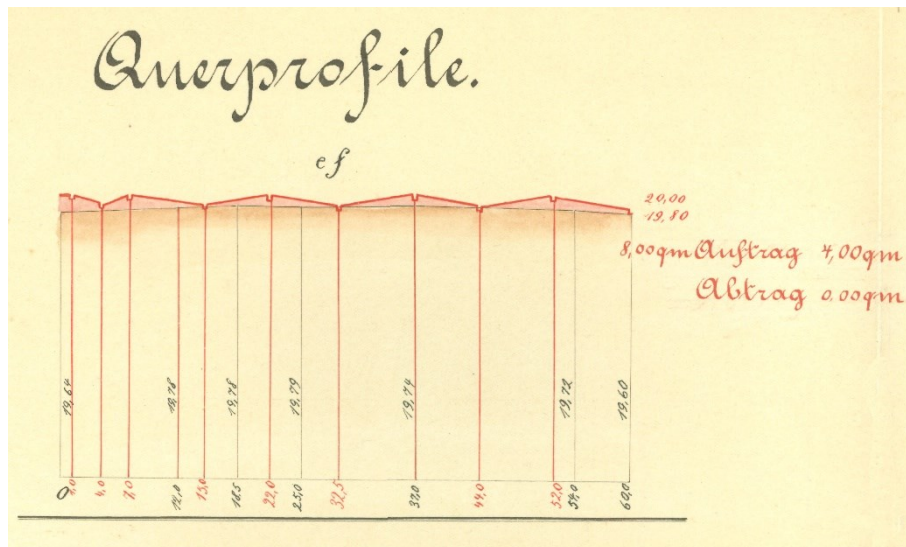


Figure 4. Detail showing cross-sections of the system from Figure 3 (P. Langhans, 1909)

3. Suderburger ridge cultivation in the Lüneburg Heath

Ridge cultivation, as a specific method of meadow management, was already known before 1819 in other parts of Europe, in other regions of what would later become the German Empire, and probably also in the Lüneburg Heath. It is no longer possible to ascertain exactly how much, or what specifically, Christoph Hillmer – as the ‘inventor’ of the Suderburg ridge system – knew about ridge construction in other regions. He probably learnt of the basic principle and then, through experimentation, developed the ‘Suderburg ridge system’, adapted to the conditions of the Lüneburg Heath. The Suderburg ridges are characterised by the fact that they are relatively narrow, ranging from 7 to 12 metres. As with other inventions, this development spanned a longer period, probably several years. In 1819, Hillmer applied the various lessons learnt in an optimised manner when creating a new irrigated meadow for the district bailiff Helmrich.

Two years later, this meadow yielded a particularly good hay harvest, with a yield eight times higher than usual. This led to a great demand for the relevant expertise and a desire to redesign one’s own meadows accordingly or to have them redesigned.

As already explained, irrigation enabled the meadows to be enriched with nutrients. These nutrients are present either in dissolved form or bound to suspended matter in the water. The effect on the meadows depends on the water used and the local soils. Textbooks repeatedly emphasise the fertilising effect of meadow irrigation. From today’s perspective, the fertilising effect must have been minimal, particularly in the Lüneburg Heath, as the question arises as to what sources of nutrients were actually available to enrich the water bodies with nutrients. Human and animal faeces were collected and used directly to fertilise gardens and fields. The fields themselves were generally not situated directly alongside the water bodies; meadows were usually found in these areas, so that nutrient runoff from the fields was also unlikely. A fertilising effect from suspended solids is particularly to be expected during flood events. As water seeps away quickly in the sandy soils and the concentration of runoff in the flat landscape increases only slowly, flooding in the Lüneburg Heath is not very pronounced. Flooding of the irrigation ridges when water levels rose above the irrigation channels was also generally undesirable, as this could easily damage the earthen channels. By opening the sluice gates in the watercourses, the discharge of floodwater into the channels could be prevented. The fertilising effect would therefore have been minor overall compared with the present-day situation, but would nevertheless have been significant for the people. A detailed discussion of the issue of fertilisation via irrigation water can be found in (Grottian, 2001) and (Grottian et al., 2004).

However, the other positive effects of meadow irrigation were probably more significant than the meadow farmers of the time realised. In spring, the soil was protected from night-time frosts, allowing the growing season to begin earlier and be extended by irrigation in autumn. Meadow irrigation also helped to control pests such as mice and moles. Valuable, nutrient-rich meadow grasses and herbs were promoted by irrigation, whilst weeds were suppressed. Undesirable substances (such as tannins or iron ochre) were washed out, thereby improving the soil in the long term.

The main significance of meadow irrigation in the Lüneburg Heath certainly lay in the repeated moistening of the soil, particularly during dry summers, but also in the drainage of waterlogged areas. Overall, the various positive effects of meadow irrigation justified the enormous effort involved. This effort was required both in the construction and in the operation of the systems.

Figure 5 shows meadow construction trainees at work on a wooden sluice gate. These sluice gates were used to dam up the water, divert it into the main irrigation ditches and, from there, distribute it across the ridges via further canals where necessary. These sluice gates had to be operated, regularly maintained and replaced. The distribution of water to the various irrigated meadows had to be constantly readjusted.

Although it involved a great deal of manual labour, the Suderburg ridge construction method, following its development from 1819 onwards, spread rapidly; some of the Suderburg meadow farmers travelled as far as Russia to lay out irrigated meadows using the Suderburg method.

Surveying the original terrain and planning an optimised irrigation system using the 'Rückenbau' method was one of the most challenging tasks facing the meadow irrigation specialists. Figure 6 shows pupils from the Suderburg meadow irrigation school carrying out maintenance work on the irrigation channels in the college's own demonstration meadow.



Figure 5. Meadow-irrigation students repairing a sluice gate (c. 1930) (KHG Baumgarten Collection)



Figure 6. Meadow-irrigation students working on a meadow (c. 1930) (KHG Baumgarten Collection)

The so-called ‘Suderburg meadow knife’ was used in particular for trimming the edges. Such a meadow knife, along with a drainage spade – which was of great importance for drainage – are depicted in the coat of arms of the municipality of Suderburg, together with the stylised church tower. The inclusion of these two meadow-making tools in the municipality’s coat of arms demonstrates the great significance that meadow cultivation held for the community.

Another tool used in meadow cultivation was the meadow axe, which was widespread throughout Europe and was used in particular for digging ditches in heavy soils and for breaking up heavily rooted tussocks of grass.

4. Meadow Irrigation today

With the widespread introduction of artificial fertiliser into agriculture, the reliance on animal manure ceased, and with it the need for meadow cultivation to increase hay yields. Of the numerous systems, only a few remnants remain today; most were abandoned by the end of the Second World War at the latest, as the land was adapted to the requirements of modern agriculture.

In 2023, traditional irrigation in Europe was finally recognised by UNESCO as an Intangible Cultural Heritage of Humanity, largely on the initiative of Christian Leibundgut. Traditional irrigation is understood here to mean gravity-fed irrigation, in conjunction with the community of participating farmers necessary for its implementation. Today, the International Centre for Traditional Irrigation in Europe (IZTB) serves as the umbrella organisation for the various local initiatives centred on meadow irrigation.

On a few plots in north-eastern Lower Saxony, the irrigation ridges are still visible under favourable conditions (Figure 8). These areas should not be confused with the agricultural land in the marshlands, which can give a similar impression due to the dense network of drainage ditches and the long, narrow plots. Even though meadow irrigation no longer plays a role today, north-east Lower Saxony is the region in Germany with the highest level of irrigation. Around 370,000 ha (Bernhardt et al., 2025) – equivalent to more than 45 per cent of all irrigated land in Germany – are located in Lower Saxony, and within this federal state, the majority of this land is in north-eastern Lower Saxony, as reliable arable yields cannot be achieved on the sandy soils without additional water supply. This, too, demonstrates just how essential meadow irrigation was in this region.



Figure 7. Remnants of old irrigation meadows still preserved in the countryside today

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REVITALISING THE DOUGLAS WEIR IN SOUTH AFRICA: A CATALYST FOR RURAL LIVELIHOODS, ECONOMIC GROWTH AND ECO-TOURISM DEVELOPMENT

REVITALISATION DU BARRAGE DE DOUGLAS EN AFRIQUE DU SUD: UN CATALYSEUR POUR LES MOYENS DE SUBSISTANCE RURAUX, LA CROISSANCE ÉCONOMIQUE ET LE DÉVELOPPEMENT DE L'ÉCOTOURISME

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ABSTRACT

The Douglas Weir is one of South Africa's oldest operational water infrastructure assets that continues to supply water for irrigation, domestic use, and local water treatment for surrounding communities. Its revitalisation offers an opportunity to strengthen environmental, social, and economic benefits by repositioning the structure as an asset for ecological restoration, sustainable water management, heritage tourism, and rural livelihood development. As an important weir in one of South Africa's driest regions, it can continue to support local resilience and adaptation initiatives. The successful revitalisation of the Douglas Weir may also provide lessons for other heritage irrigation sites in South Africa and for broader adaptation to increasing variability in natural watercourses. This narrative scoping review examines opportunities to use the Douglas Weir to improve local livelihoods, promote eco-tourism, attract investment, and enable innovation in water and land management. The study highlights the weir as a historically significant irrigation structure with potential to contribute to national development, particularly after its recognition as a World Heritage Irrigation Structure (WHIS) by the International Commission on Irrigation and Drainage (ICID) in 2024. The goal is to develop a sustainable, technologically informed approach to managing and revitalising the weir to enhance existing benefits and identify new uses. Key opportunities include: (a) developing the weir as a heritage and tourism hub linked to local economic development, (b) strengthening its role in water regulation for irrigation, agricultural productivity, and food security, and (c) creating employment opportunities, reducing poverty, and improving access to purified water for surrounding communities.

RÉSUMÉ

Le barrage de Douglas est l'un des plus anciens ouvrages hydrauliques opérationnels d'Afrique du Sud, continuant à fournir de l'eau pour l'irrigation, les usages domestiques et le traitement local de l'eau au profit des communautés environnantes. Sa revitalisation offre l'occasion de renforcer les bénéfices environnementaux, sociaux et économiques en repositionnant l'ouvrage comme un atout pour la restauration écologique, la gestion durable de l'eau, le tourisme patrimonial et le développement des moyens de subsistance ruraux. En tant qu'important barrage situé dans l'une des régions les plus sèches d'Afrique du Sud, il peut continuer à soutenir les initiatives locales de résilience et d'adaptation. La revitalisation réussie du barrage de Douglas pourrait également fournir des enseignements pour d'autres sites patrimoniaux d'irrigation en Afrique du Sud et pour une adaptation plus large à la variabilité croissante des cours d'eau naturels. Cette revue narrative de portée examine les possibilités d'utiliser le barrage de Douglas pour améliorer les moyens de subsistance locaux, promouvoir l'écotourisme, attirer des investissements et favoriser l'innovation dans la gestion de l'eau et des terres. L'étude met

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en évidence le barrage comme un ouvrage d'irrigation historiquement important, susceptible de contribuer au développement national, en particulier après sa reconnaissance comme Structure d'irrigation du patrimoine mondial (WHIS) par la Commission internationale des irrigations et du drainage (CIID) en 2024. L'objectif est de développer une approche durable et éclairée par la technologie pour gérer et revitaliser le barrage afin de renforcer les bénéfices existants et d'identifier de nouveaux usages. Les principales possibilités comprennent : (a) développer le barrage comme pôle patrimonial et touristique lié au développement économique local, (b) renforcer son rôle dans la régulation de l'eau pour l'irrigation, la productivité agricole et la sécurité alimentaire, et (c) créer des possibilités d'emploi, réduire la pauvreté et améliorer l'accès à l'eau purifiée pour les communautés environnantes.

Keywords: Douglas Weir, climate resilience and adaptation, agricultural water management, water security, food security, sustainable development

1. Introduction

The Douglas Weir, located at the confluence of the Vaal and Orange Rivers near Douglas (Figure 1) in the Northern Cape Province, South Africa, represents one of the country's most significant water infrastructure assets. Originally established in the late nineteenth century and subsequently upgraded over the years, the weir has played a pivotal role in supporting irrigation, agricultural production, and rural development in an otherwise water-scarce region (Moolman, 1946). The weir is now a historic 134-year-old irrigation structure, commissioned in 1890-91, and was recently recognised as a World Heritage Irrigation Structure by the International Commission on Irrigation and Drainage (ICID) (https://icid-ciid.org/award/his_details/215). As a result, the Douglas Weir has gained renewed national and international attention. The weir regulates water on the Vaal River just upstream of the confluence of the Vaal and Orange rivers (Pululu et al., 2015). This concrete asset spans 1,063 meters, reaching a height of 10 meters, and supplies vital irrigation and drinking water. Apart from its historic importance for irrigation, the weir works alongside the upgraded Douglas Water Treatment Works to supply purified municipal water to local communities



Figure 1. Agricultural irrigation activities around the Douglas Weir, located at the confluence of the Orange and Vaal Rivers

Floodwaters once damaged the original structure, but it was rebuilt several times before the modern configuration was developed and raised in 1977 (https://icid-ciid.org/award/his_details/215). For more than a century, the weir has expanded its irrigation scope as settlements have grown around it, improving water and food security, creating employment, and supporting rural development. Its designation as a World Heritage Irrigation Structure recognizes not only engineering excellence but also its contribution to rural development and agricultural transformation in the area. This historical narrative of the Douglas Weir provides a strong foundation for heritage, eco-tourism, and educational initiatives that can generate new revenue streams for local communities.

Water infrastructure has historically shaped settlement patterns, agriculture, and economic development across South Africa and elsewhere (Swatuk, 2010). Dams, canals, and pipelines transfer scarce water from wetter catchments to drier agricultural, urban, and industrial areas, supporting production and settlement in regions that would otherwise face severe water constraints. In semi-arid regions such as the Northern Cape, reliable access to water remains fundamental to food production, employment creation, and rural livelihoods (Msweli et al., 2025). As highlighted earlier, the Douglas Weir, situated at the confluence of the country's major rivers, the Vaal and Orange Rivers, flowing from east to west, has served as a critical water diversion and irrigation structure for more than 134 years. The weir currently supports irrigation across approximately 8,113 hectares of agricultural land and forms an important component of regional water supply systems. Its recognition as South Africa's first World Heritage Irrigation Structure (WHIS) presents a unique opportunity to reposition the site as both a developmental asset and a tourism destination.

Revitalising historic irrigation weirs and low-head diversion structures can restore community water security, strengthen climate-resilient local agriculture, and support the rehabilitation of river ecosystems (Hester et al., 2026). These traditional masonry or rock-fill barriers can also improve local groundwater recharge, moderate flood peaks, and support rural livelihoods with a lower material and energy footprint than large modern concrete dams when appropriately designed and maintained (Kebede et al., 2024) (Table 1). Core benefits include: (a) improving water security by capturing scarce runoff and raising local stream levels for gravity-fed irrigation during dry periods, (b) increasing groundwater recharge by slowing surface runoff and allowing water to percolate into local aquifers, (c) mitigating flooding by reducing peak flow velocities and downstream erosion, (d) supporting biodiversity conservation by creating stable micro-habitats and pools that sustain aquatic life, flora, and fauna through dry seasons, and (e) preserving cultural heritage by protecting indigenous engineering knowledge and community-led watershed management traditions.

Table 1. Modern integration of ancient weirs against original constraints (after Kebede et al., 2024)

Feature	Ancient/Traditional Weirs	Modern Concrete Dams
Materials	Local stone, timber, and compacted earth	Heavy reinforced concrete and steel
Environmental Impact	Minimal disruption; allows controlled overflow	High fragmentation of river ecosystems
Maintenance	Community-managed, low-cost local labour	Centralized, expensive mechanized upkeep
Lifespan Adaptation	Flexible; naturally absorbs minor structural shifts	Rigid; prone to catastrophic failure if undermined

Revitalising ancient irrigation weirs is generally sustainable when combined with modern ecological science and local community governance, offering low-energy water retention, climate resilience, and restored rural livelihoods, though poorly managed projects risk siltation, disrupted river flows, and habitat damage (Wang & He, 2022). Revitalising such weirs involves restoring stone or earthen diversion structures using a blend of traditional craftsmanship and modern ecological engineering. Key steps include structural repair using local materials, community-based participatory governance, sediment management, and nature-based solutions to enhance climate resilience and downstream river health.

Maintaining ancient weirs is equally important for community governance and participation, as local communities retain stewardship through well-structured traditional water user associations or farmer cooperatives, as they take full ownership of the weirs through self-funded maintenance schedules and water allocation (Lema, 2025). The communities also contribute to participatory mapping by combining indigenous historical knowledge of local rainfall-runoff patterns with modern hydrological surveying. Importantly, ancient irrigation structures are key to policy recognition by securing legal recognition for ancestral water rights and community-led conservation frameworks.

Restoring historic earthen and stone water channels, such as the centuries-old acequias of Spain and New Mexico, demonstrates that traditional systems can function as efficient nature-based water management solutions (da-Silva-Branco et al., 2026). Evidence from these systems indicates that a substantial proportion of channelled water may intentionally seep into the soil profile and recharge local aquifers, even though the reported 33% recharge estimate should be linked to a specific source (Bruijnzeel et al., 2025). Recognising and revitalising ancient weirs is not limited to engineering rehabilitation, but also supports a broader development vision that integrates sustainable agriculture, rural entrepreneurship, heritage preservation, environmental conservation, eco-tourism, and community empowerment.

In South Africa, revitalising the ancient irrigation weirs aligns with the National Development Plan (NDP), Sustainable Development Goals (SDGs), and national objectives of inclusive economic growth, climate resilience, agricultural development, employment creation, and rural development (NDP, 2013). This study explores how revitalising the Douglas Weir can go beyond its traditional irrigation function to become a catalyst for inclusive rural development, local economic transformation, environmental restoration, and eco-tourism growth. It argues that an integrated development model combining water security, heritage, cultural and nature conservation, agricultural innovation, community participation, and sustainable tourism can unlock significant socioeconomic benefits for communities within the Siyancuma Local Municipality and the wider Northern Cape Nama-Karoo biome region.

2. Prospects to improve livelihoods through revitalised weirs

Agriculture remains the backbone of the local economy around the Douglas Weir. Revitalising the weir strengthens irrigation reliability and improves water management efficiency, increases crop yields, diversifies into high-value crops, expands horticultural enterprises, improves livestock production, and enhances climate resilience. Incorporating modern irrigation technologies such as precision irrigation, smart monitoring systems, and water-efficient practices can reduce wastage while increasing productivity, key elements of agricultural water management and pathways to transform smallholder agriculture (Kumar et al., 2024). Rural agriculture and smallholder irrigation schemes should be a priority in irrigation revitalisation plans to ensure equitable access to water resources and agricultural opportunities.

Therefore, revitalising rural irrigation weirs enhances livelihoods by securing water for gravity-fed irrigation, livestock, and local ecosystems. This restores reliable crop production, mitigates drought, boosts household incomes, and creates community-level jobs through water management and local agro-processing (Table 2).

Rehabilitating irrigation weirs transforms rural livelihoods by securing consistent water supply for year-round crop production. This process boosts food security, creates local jobs, and generates stable household income, turning vulnerable subsistence farming communities into resilient, self-sustaining local economies. However, these initiatives have challenges (Timsina & Weerahewa, 2023). Revitalising irrigation weirs requires balancing structural civil repairs with institutional support. Primary challenges include severe infrastructure backlogs, climate-induced hydrological unpredictability, insecure land tenure, and a lack of local technical expertise. Sustainable recovery relies on comprehensive modernisation, inclusive community water governance, and adaptive, decentralized investments (Daokoru-Olukole et al., 2026).

Table 2. Benefits of revitalising ancient irrigation weirs

Benefit	Sub-sector	Explanation
Agricultural productivity and food security	Reliable irrigation	Restored weirs raise upstream water levels to feed gravity-based canals, allowing smallholders to transition from erratic rain-fed farming to consistent multi-season crop production.
	Crop diversification	Stable water access enables farmers to grow high-value vegetables, legumes, and fodder instead of low-yield staple grains.
	Nutritional security	Local nutrition gardens and orchards become viable near the water source, directly improving household dietary diversity.
Economic growth and job creation	Direct employment	Repair and construction work injects immediate income into vulnerable communities via cash-for-work programmes.
	Surplus income	Higher crop yields allow smallholders to sell produce on local markets, turning subsistence plots into commercial enterprises.
	Diversified livelihoods	Reliable water supply supports secondary activities such as aquaculture and livestock rearing, insulating families against total harvest failures.
Environmental and climate resilience	Drought mitigation	Low-barrier weirs buffer against erratic rainfall and prolonged dry spells by maintaining local surface water storage and recharging groundwater.
	Ecosystem restoration	Controlled water spreading helps stabilize degraded valleys, reduce soil erosion, and restore vegetative cover in arid or semi-arid rural landscapes.

2.1 Job creation and rural enterprises

Irrigation weirs stabilise river water levels and divert flow for agriculture, serving as vital anchors for rural economic growth (Kabwe et al., 2023). They create year-round employment via farming jobs, enable small-scale agribusinesses to consistently supply both formal and informal markets, and reduce poverty in drought-prone rural settlements. Revitalising the Douglas Weir generates employment across construction, maintenance, agriculture, tourism, environmental management, and the service sectors. Short-term jobs may arise from civil works, canal cleaning, sediment removal, fencing, signage, landscaping, visitor facility construction, and water-quality monitoring. Longer-term employment can be created through irrigation scheduling services, pump and canal maintenance, farm labour, agro-processing, local transport, and tourism via guiding, catering, accommodation, craft production, security, and site management. Prioritising local procurement and labour-intensive work packages would ensure that a larger share of revitalisation expenditure remains within surrounding communities. Adopting novel technologies in the smallholder irrigation schemes attracts the youth to agriculture and creates employment opportunities.

Rural enterprises linked to the weir could include vegetable production, livestock feed production, seedling nurseries, small-scale fisheries, packaged local produce, farm stalls, irrigation equipment repair, riverfront recreation services, homestays, cultural performances, and local food outlets. Enterprise incubation should be connected to market access, business training, cooperative development, quality standards, basic bookkeeping, and digital marketing. This would allow the weir to function not only as a water asset, but also as a platform for rural entrepreneurship and diversified household income. These benefits transform smallholder irrigation schemes into fully fledged commercial farming enterprises (Table 3).

Table 3. Potential economic and employment opportunities from revitalising the Douglas Weir

Opportunity	Enterprise	Explanation
Direct Job Creation	On-farm employment	Reliable water allows continuous, multi-season crop production, replacing temporary seasonal labour with permanent farm worker and manager positions.
	Infrastructure upkeep	Local communities find ongoing work maintaining canals, clearing silt, and repairing masonry or gates around the weir pool.
	Value-chain roles	Transport, sorting, packaging, and local trading create secondary jobs for youth and women outside the direct crop field.
Growth of Rural Enterprises	Crop diversification	Predictable water access allows smallholders to transition from low-margin subsistence staples to high-value commercial crops.
	Agripreneurship	Smallholders transition into commercial growers, supplying distribution networks with local fresh produce.
	Service micro-enterprises	Local repair workshops, pump mechanics, input suppliers, and tool vendors emerge to support nearby clustered farming communities.

2.2 Youth and women empowerment

Irrigation weirs empower women and youth by providing a reliable, year-round water supply that unlocks agricultural income, creates jobs, and slashes the time-consuming labour burden of manual water collection (Bryan & Mekonnen, 2023). By raising and diverting water upstream, these small-scale infrastructure projects stabilize rural economies, build climate resilience, and open pathways for marginalized groups to assume leadership roles in local resource governance. A deliberate youth and women empowerment strategy is essential to ensure that these revitalisation benefits are inclusive and transformative. Young people can be trained as irrigation technicians, drone and sensor operators, tour guides, heritage interpreters, environmental monitors, digital marketers, and enterprise managers (Mathinya et al., 2023). Women can be supported through targeted access to irrigated plots, land tenure, agro-processing facilities, tourism businesses, craft markets, catering services, cooperatives, and leadership roles in water governance structures. These measures shift the revitalisation from infrastructure rehabilitation to broader social and economic empowerment of the surrounding communities.

Empowerment should be supported by practical measures such as reserved enterprise spaces, preferential local procurement, mentorship programs, accredited training, startup grants, cooperative financing, and representation in decision-making forums. Schools, technical colleges, universities, agricultural extension services, and the Water Research Commission (WRC) can enhance skills development by connecting the site to programmes focused on water literacy, climate adaptation, heritage conservation, and rural innovation. This would create a pipeline of local skills to sustain the weir's technical, social, and economic functions over time.

3. Economic benefits

3.1 Economic development opportunities

Irrigation weirs boost economic development by securing water availability for high-value crops, preventing dry-season harvest failures, creating steady rural jobs, and powering local agro-industries that drive rural growth (Zhong et al., 2024). The Douglas Weir, for example, can stimulate economic development by improving agricultural output, expanding value chains, upgrading infrastructure, and increasing visitor spending. Reliable irrigation supports horticulture, fodder production, small livestock

enterprises, and local food markets, while agro-processing adds value through drying, packaging, milling, juicing, cold storage, and branding of local produce. Improved roads, signage, digital connectivity, water services, and public amenities around the site would also benefit residents and enterprises beyond the tourism sector.

A cluster-based development approach could link farmers, tourism operators, training providers, local government, water institutions, and investors into a coordinated rural development platform. Such a platform could promote local branding around water heritage, climate-resilient agriculture, Orange-Vaal River landscapes, and community enterprises. With transparent and coherent governance and market-oriented planning, the weir could become an anchor for inclusive local economic growth rather than a single-purpose irrigation structure. This Nama-Karoo biome in the Northern Upper Karoo vegetation unit within the Southern Temperate Highveld freshwater ecoregion has many unique attributes to be developed as tourist attractions. Some of these key biodiversity traits include the complex mix of C4 grasses and dwarf deciduous shrubs (known as Karoo bossies), with more than 120 endemic plant species (daisies and Mesembryanthemaceae); historically nomadic wild game such as springbok; specialised micro-fauna including reptiles, insects and birds (Cowling et al., 1998; Rubin et al., 2001).

Recognising the Douglas Weir as a World Heritage Irrigation Structure created a platform to develop a heritage-based tourism economy linked to water, agriculture, engineering history, river ecology, and rural livelihoods (Ricart et al., 2019). A revitalised site could include guided heritage walks, interpretive signage, a small visitor and learning centre, school excursions, agro-tourism routes, local craft markets, and demonstration plots that showcase efficient irrigation, climate-smart agriculture, and water conservation practices. These activities would diversify the local economy beyond primary agriculture while creating opportunities for youth guides, small enterprises, accommodation providers, transport operators, food vendors, and community cooperatives.

For tourism development to be sustainable, the Douglas Weir should be positioned as part of a broader Orange-Vaal River corridor experience rather than as an isolated structure. Linking the weir to existing agricultural landscapes, local cultural assets, river-based recreation, conservation areas, and community enterprises would increase visitor appeal and spread benefits across the Siyancuma Local Municipality. Such an approach would also strengthen public appreciation of water infrastructure by showing how historic irrigation systems continue to support food production, domestic water supply, rural employment, and adaptation to climate variability.

3.2 Heritage economy

The heritage economy refers to economic activity generated through the conservation, interpretation, and responsible use of cultural, historical, and natural assets (Zhong et al., 2024). The Douglas Weir's heritage value lies in its age, engineering history, role in irrigation development, contribution to settlement patterns, and continued service to local communities. This value can be translated into economic opportunity through guided tours, exhibitions, archival displays, educational materials, heritage and cultural festivals, branded local products, research visits, and partnerships with schools, universities, museums, and tourism authorities.

A heritage economy must be managed carefully, allowing commercial activities to strengthen rather than erode the weir's historical significance. Interpretation should recognise local farming communities, water users, engineers, municipal actors, and broader river histories, while avoiding a narrow focus on the structure alone. Revenue from heritage activities could support maintenance, youth training, community projects, environmental monitoring, and visitor services, creating a virtuous cycle in which conservation and local development reinforce one another.

3.3 Eco-tourism development potential

Irrigation weirs boost eco-tourism by creating scenic wetland habitats, enabling water-based recreation such as canoeing, supporting birdwatching, and preserving historical rural heritage (Ahn et al., 2014). The Douglas Weir has strong eco-tourism potential because it combines river scenery, irrigation

heritage, agricultural landscapes, biodiversity, and educational value. Possible activities include birdwatching, river-viewing platforms, interpretive walking routes, school water-education programmes, agro-tourism visits, photography points, canoeing or low-impact recreational activities (where safe and permissible), and demonstrations of water-efficient farming. These opportunities can appeal to domestic tourists, researchers, school groups, heritage visitors, agricultural delegations, and travellers moving through the Northern Cape to other tourism destinations such as the Augrabies Waterfall, Quiver Tree Forest, and Namaqualand spring flowers.

Eco-tourism development should remain low-impact and compatible with water security and ecological protection. Visitor infrastructure should use appropriate siting, waste management systems, safety controls, erosion prevention, environmental education, and community-based enterprise models. If planned responsibly, eco-tourism can generate local revenue while strengthening awareness of river conservation, wildlife, climate adaptation, water-use efficiency, and the importance of maintaining historic irrigation infrastructure.

4. Governance, financing, and implementation pathway

Successful revitalisation will require a coordinated governance model involving the Orange-Vaal Water Users Association, Siyancuma Local Municipality, provincial and national water institutions, agricultural organisations, tourism agencies, research institutions, traditional and community representatives, and private investors. The governance model should clarify responsibilities for structural maintenance, water allocation, visitor management, environmental compliance, safety, revenue sharing, and local enterprise development. A formal stakeholder platform would help align infrastructure rehabilitation with water services, irrigation performance, heritage conservation, and tourism planning.

Financing should combine public infrastructure investment, water-user contributions, climate adaptation funding, research and innovation grants, tourism development support, and carefully structured private-sector partnerships. Priority actions include a technical condition assessment of the weir and canals, hydrological and ecological baseline studies, rehabilitation of priority infrastructure, installation of monitoring technologies, development of training programmes for water users and local enterprises, and preparation of a heritage and tourism management plan. These actions should be phased so that urgent water security and safety needs are addressed first, while longer-term tourism and enterprise opportunities are developed without compromising the weir's primary water management function.

5. Environmental sustainability, conservation, and climate adaptation

Environmental sustainability must be at the heart of revitalising the Douglas Weir, as it is situated within a dynamic river system that supports agriculture, municipal water supply, aquatic habitats, riparian vegetation, and downstream users (Stuart et al., 2019). The rehabilitation process should consider river health, which includes maintaining environmental flows, balancing sediment, protecting water quality, controlling erosion, and restoring degraded riverbanks. Conservation actions may include removing invasive alien plants, stabilising riparian zones with indigenous vegetation, protecting wetland and floodplain areas, and monitoring aquatic biodiversity and water quality. These measures would ensure that the weir contributes to ecological restoration rather than functioning only as an irrigation and water-supply asset.

5.1 Climate change adaptation

Climate change is expected to increase pressure on semi-arid water systems through higher temperatures, more variable rainfall, intensified droughts, and episodic floods. The Douglas Weir could enhance adaptation by improving local water retention, supporting reliable irrigation during dry periods, reducing rural households' vulnerability to rainfall variability, and strengthening the resilience of agricultural value chains. Adaptation planning should include drought operating rules, flood preparedness, seasonal water allocation planning, early-warning systems, climate-informed irrigation scheduling, and continuous hydrological monitoring. These interventions would help farmers, water managers, and local authorities respond proactively to changing river and water supply conditions.

5.2 Green infrastructure and nature-based solutions

Green infrastructure should complement engineering rehabilitation by using natural systems to improve water management, reduce risk, and enhance ecological value (Nhamo et al., 2017; Stefanakis, 2019). Appropriate interventions include vegetated buffer strips along canals and riverbanks, constructed wetlands for polishing runoff, permeable visitor pathways with shaded rest areas using indigenous trees, erosion-control planting, sediment traps, and riparian conservation zones. These measures can reduce runoff pollution, moderate local micro-climate temperatures, improve habitat connectivity, protect soils, and enhance the visitor experience. A green infrastructure approach would also reinforce the site's identity as a climate-resilient heritage and eco-tourism destination.

5.3 Governance and stakeholder partnerships

Environmental sustainability and climate adaptation will require strong governance and durable partnerships across institutions. A dedicated Douglas Weir revitalisation forum could bring together the Department of Water and Sanitation (DWS), WRC, Orange-Vaal Water Users Association, Siyancuma Local Municipality, provincial environmental and tourism authorities, local farmers, community organisations, conservation groups, universities, private investors, and youth and women-led enterprises, together with other interested parties. The forum should coordinate planning, funding, monitoring, compliance, skills development, and benefit-sharing. Transparent stakeholder partnerships would reduce duplication, improve accountability, and ensure that ecological, social, cultural, and economic objectives are managed as part of one integrated programme. Table 4 summarises the sustainability themes for the Douglas Weir revitalisation.

Table 4. Summary of sustainability themes for Douglas Weir revitalisation

Sustainability theme	Primary contribution	Operational focus
Water security and efficient irrigation	Improves reliable water availability for irrigation, domestic supply support, and drought resilience in a semi-arid landscape.	Hydrological monitoring, irrigation scheduling, canal maintenance, and water-use efficiency technologies.
Ecological restoration and conservation	Protects river health, riparian vegetation, biodiversity, water quality, and downstream ecosystem functions.	Environmental flows, invasive alien plant control, erosion stabilisation, water-quality testing, and biodiversity monitoring.
Climate adaptation and risk reduction	Reduces vulnerability to droughts, variable flows, heat stress, floods, and agricultural production shocks.	Early-warning systems, drought operating rules, flood preparedness, adaptive infrastructure design, and seasonal planning.
Inclusive livelihoods and local enterprise	Links water infrastructure revitalisation to employment, agro-processing, youth and women empowerment, and rural income diversification.	Local procurement, enterprise incubation, skills training, cooperative development, and transparent benefit-sharing.
Heritage and eco-tourism	Converts historical recognition into education, tourism, cultural interpretation, and conservation-oriented local revenue.	Interpretive signage, guided routes, visitor safety, school programmes, and community tourism and accommodation enterprises.
Governance and institutional collaboration	Ensures that social, environmental, economic, and technical objectives are coordinated through accountable partnerships.	Stakeholder forum, clear operating mandates, compliance processes, revenue-sharing rules, and monitoring and evaluation.

6. Risks, safeguards, and sustainability considerations

Revitalisation must manage several risks as engineering interventions could unintentionally alter flow patterns, increase sedimentation, affect aquatic habitats, or reduce downstream water availability if they are not guided by sound hydrological and environmental assessment. Tourism development could also produce uneven benefits if local communities are not involved in ownership, employment, and decision-making. In addition, climate change may increase the frequency of droughts, floods, and extreme flow events, raising the importance of adaptive infrastructure design and continuous monitoring.

Safeguards should include environmental flow protection, sediment management, water quality monitoring, flood-risk assessment, public safety measures, transparent benefit-sharing arrangements, and inclusive participation by farmers, residents, youth, women, and local businesses. The revitalisation process should also preserve the weir's historical characteristics while introducing modern technologies in ways that remain compatible with the site's heritage value. A monitoring and evaluation framework should track irrigation reliability, household and enterprise benefits, employment creation, visitor numbers, ecological indicators, water quality, and community satisfaction.

7. Conclusion

The Douglas Weir represents more than a historic irrigation structure; it is a strategic rural development asset located at the intersection of water security, agricultural production, environmental sustainability, climate adaptation, heritage conservation, local enterprise development, youth and women empowerment, and eco-tourism growth. Its long operational history, continued role in irrigation and water supply, and international heritage recognition provide a strong foundation for a revitalisation programme that can generate practical benefits for surrounding communities while protecting river ecosystems. If managed through an integrated and participatory model, the weir can support food security, improve livelihoods, stimulate rural enterprises, create decent work, expand the heritage economy, strengthen climate resilience, and promote conservation-oriented development along the Orange-Vaal River corridor. Revitalising the Douglas Weir should not be treated as a narrow infrastructure rehabilitation exercise. Rather, it should be framed as a place-based development strategy that integrates technical rehabilitation, efficient irrigation, domestic water support, ecological restoration, green infrastructure, heritage interpretation, job creation, rural enterprise incubation, inclusive governance, stakeholder partnerships, and low-impact tourism. With appropriate investment, safeguards, skills development, environmental monitoring, and institutional coordination, the Douglas Weir can become a nationally significant demonstration site for how historic water infrastructure can contribute to sustainable development in semi-arid rural regions.

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BEELA-BATTI: A UNIQUE HERITAGE IRRIGATION SYSTEM IN SOMPETA AREA OF ANDHRA PRADESH, INDIA

BEELA-BATTI: UN SYSTÈME D'IRRIGATION PATRIMONIAL UNIQUE DANS LA RÉGION DE SOMPETA EN ANDHRA PRADESH, INDE

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ABSTRACT

The coastal wetland near Sompeta in north Andhra Pradesh, India is a system of three water bodies connected in series. It is spread over an area of 3,200 acres closer to the Bay of Bengal. Pedda Beela is the only fresh water body at the head of the system, while two downstream water bodies being brackish. A traditional irrigation practice, locally known as Batti (meaning channel), exists on Pedda Beela wetland. Farmers have dug gently sloping channels radially outward from inside the Pedda Beela to facilitate water flow from the wetland by gravity. The water that reaches the agricultural lands through Battis is pumped out and used for irrigating crops. Each Batti channel is maintained by a group of 3–10 farmers, irrigating 10-15 acres. Paddy, vegetables, and flowers are cultivated in the agriculture lands using the water depending on the soil type and agricultural season. A total of 64 Batti channels with an approximate length of 38 km, provide irrigation to a gross area of 800 acres. The seepage to groundwater augments irrigation water availability in wells and ponds to around 1200 acres of land in the vicinity. Current work documents the Beela-Batti heritage irrigation system in detail.

RÉSUMÉ

La zone humide côtière près de Sompeta, dans le nord de l'Andhra Pradesh, en Inde, est un système de trois plans d'eau reliés en série. Elle s'étend sur une superficie de 3 200 acres, proche de la baie du Bengale. Pedda Beela est le seul plan d'eau douce au début du système, tandis que les deux autres plans d'eau en aval sont saumâtres. Une pratique d'irrigation traditionnelle, connue localement sous le nom de Batti (qui signifie canal), existe dans la zone humide de Pedda Beela. Les agriculteurs ont creusé des canaux légèrement inclinés qui s'étendent radialement à partir de l'intérieur de Pedda Beela pour faciliter l'écoulement de l'eau depuis la zone humide par gravité. L'eau qui atteint les terres agricoles par les Battis est pompée et utilisée pour irriguer les cultures. Chaque canal Batti est entretenu par un groupe de 3 à 10 agriculteurs et irrigue 10 à 15 acres. Le riz, les légumes et les fleurs sont cultivés dans les terres agricoles à l'aide de cette eau, selon le type de sol et la saison agricole. Au total, 64 canaux Batti, d'une longueur approximative de 38 km, fournissent l'irrigation à une superficie brute de 800 acres. L'infiltration dans les nappes phréatiques augmente la disponibilité de l'eau d'irrigation dans les puits et les étangs pour environ 1200 acres de terres dans les environs. Les travaux actuels documentent en détail le système d'irrigation patrimonial Beela-Batti.

Keywords: Coastal wetland, Traditional irrigation system, Gravity channels, Seepage from wetland

1. Introduction

The land area on the earth takes different physical forms, providing ecological and economic applications by virtue of its soil type, soil moisture, vegetation cover and the diversity of flora-fauna that thrive in that land. Forest lands, agriculture lands, grass lands, artificial pastures, hills, and mountains are some of the well-known land forms. Similarly, wetland is a form of land that forms with the coexistence of land and water. The ground is soggy and muddy, and it is occupied by water most part

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of the year. There are many types of wetlands around the world, called swamps, marshes, bogs, mangroves etc., depending on the type of vegetation and water.

Wetlands form over many years through different natural processes. When the rain water, after flowing over-land, gets collected in the places of lower elevation or natural depressions in the land. When it rains heavily, water quickly accumulates in these low areas and pools there. If enough water collects and stays for a long time, the ground becomes wet and muddy. Special wetland plants start growing. Over the years, mud collects at the bottom, special plants establish themselves, and a proper wetland develops.

Wetlands also form in coastal areas where streams and rivers meet the ocean. When rivers reach the ocean, they slow down and spread the water because the slope of the land flattens out. As the river slows down, it deposits sediments, sand, and plant material that it has carried from upstream areas. Over time, these materials fill up and create shallow water areas. The surplus fresh water from such wetlands goes to the ocean. The water in these areas mixes with salt from the sea because they are so close to the ocean. Special salt-tolerant plants start growing in this environment. Thus, wetlands form in these coastal areas, and they are often vital for thriving of fisheries and diverse birds and animals.

Wetlands are among the most valuable and important places of ecological significance on the earth. There are six ecological functions that exemplify the importance of wetlands:

They absorb flood peaks and protect surrounding areas from inundation. They purify the dirty and contaminated water through phytoremediation processes wetlands push saline seawater from moving inland in the coastal areas, protecting fresh water sources they are home to diverse animals, plants and microorganism. They also attract migratory birds and animals from across the globe Wetlands give local population the food for survival and materials that we use every day, such as fish, plant produce, herbs, firewood, grasses, and other raw material for building houses and sheds.

Thus, the wetlands play vital role in not only in ecological conservation, but also in meeting food needs and supporting the livelihoods of local population.

The present work documents in detail the traditional irrigation system, locally called Beela-Batti system, associated with the Sompeta wetland (18.91580, 84.60740) located in northern part of Andhra Pradesh State in India. Though the study by Sebastian et al. (2017) documented the biodiversity of the wetland, no attempt was made earlier to study and report the heritage irrigation system associated with the wetland in detail.

2. The Beela Wetland of Sompeta

India has some of the most beautiful and important wetlands in the world. These wetlands are found in different parts of India, and they are all special in their ways. Some are smaller, and some are larger. Some have freshwater in them, and some others have salt water. As per the enumeration done by Ministry of Environment, Forests and Climate Change, there are a total of 1313 wetlands in India, 110 being significant ones. Out of them, presently 101 have been recognized as Ramsar sites (Convention Secretariat 2026). A Ramsar site is a wetland site designated to be of international importance under the Ramsar Convention, also known as 'The Convention on Wetlands', an international environmental treaty signed on 2 February 1971 in Ramsar, Iran, under the auspices of UNESCO.

Kolleru lake, Chilika lake, Sundarbans and Pulicat lake are some of the larger wetlands located on the eastern coast of India and recognized as Ramsar sites. Another smaller coastal wetland in the eastern coast of India is the wetland (locally known as Beela) of Sompeta mandal, Srikakulam district in Andhra Pradesh. The traditional gravity channel (locally known as Batti) irrigation system associated with this wetland is the focus of the current study. This is a coastal natural wetland that holds fresh water flowing from its natural catchment and drains the excess of it to the Bay of Bengal.

The Beela is a system of three connected water bodies that are connected in a series and work together. The first part is called Pedda Beela; “Pedda” meaning “big” in the local Telugu language. This is the main and largest water body of the system. Peddha Beela contains freshwater throughout the year (Figure 1), which means it's not saline entire year. The second water body is called Chinna Beela; “Chinna” meaning “small” in local language. This is smaller compared to the Pedda Beela, and receives surplus water from it. The third one is a further smaller water body that is in direct contact with the Bay of Bengal and drains surplus water from the Chinna Beela into it. Together, the Beela is spread over a total area of 12.8 sq.km (3200 acres). ISRO The wetland system is mapped and included in the wetland atlas prepared by Indian Space Research Organization (ISRO 2011, pp.66-67).

Water comes into Beela from three different sources that together keep the wetland full. The first and most important source is the Mahendratana River, which originates in the mountains of eastern ghats at about 60 km distance. The Mahendratana and its streams capture run-off from the expansive mountains during the rainy season and carry it towards the Beela. During the heavy rains of monsoon season, this river brims with water and allows copious flows downstream, finally draining into Bay of Bengal. But farmers made a number of gravity diversion channels from the river upstream to divert water for irrigation purposes. The surplus water from these channels as well as the used irrigation water from farm lands drains into the Beela. Thus, during the rainy season of June to Oct, Beela is fed with rain water and the Beela stores this water throughout the year.

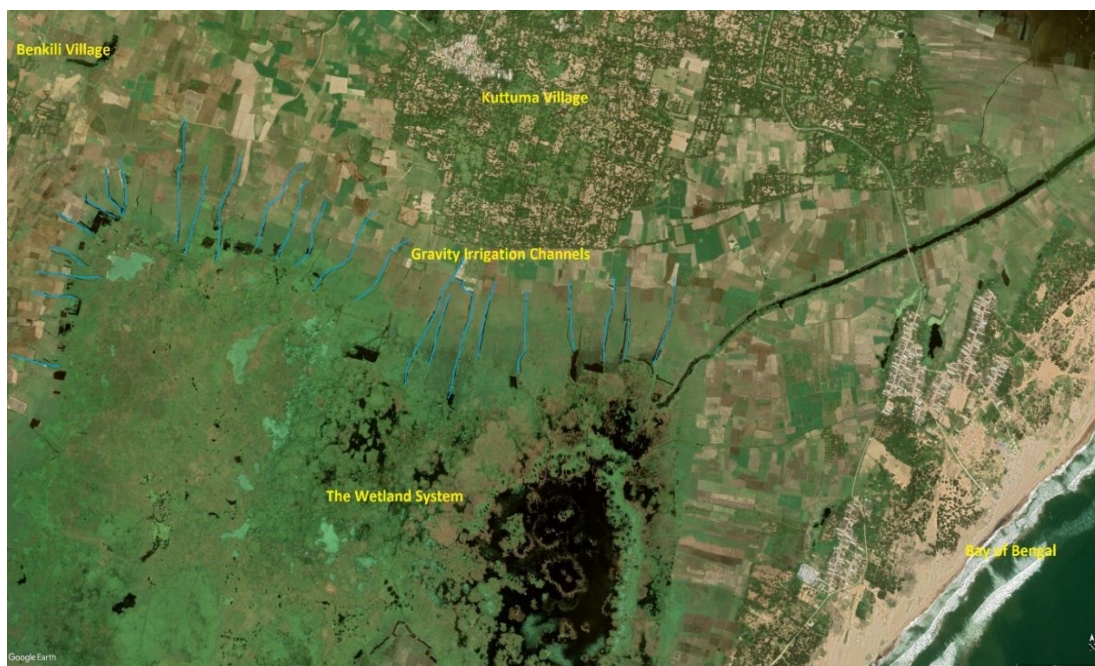


Figure 1. Location map of the wetland (Source: Google Earth Pro imagery)

The inflow to the Beela is augmented by the overland rainwater flow from the upper catchment areas as far as 40 km upstream. The excess irrigation water draining out from the command areas of the upstream Pydigam reservoir on the Mahendratana river also flows into the Beela. The major water inflow sources of the Beela as well as the outflow waterway to the Bay of Bengal are schematically shown in Figure 2.

3. The traditional Beela-Batti Irrigation System

The Beela wetland located in the northern part of Srikakulam district in Andhra Pradesh is spread over nearly 12.8 sq.km (3200 acres) of land in three administrative mandals, viz., Sompeta, Kaviti and Kanchili. The Beela has three parts of the wetland connected in series. While the upstream part, locally

called Pedda Beela, which receives the inflows from Mahendratanya river and other surface streams, is a fresh water body. The other two downstream parts are saline wetlands due to the seawater ingress. Around 33 villages with a total of nearly 90,000 population are in the immediate vicinity of this wetland system. Geographically, these villages have a common perimeter with the Beela wetland system, starting from Baruva in Sompeta mandal to Battivanipalem in Kaviti mandal.



Figure.2. The water inflow sources of the wetland

When the Beela is full of water, generally at the end of the rainy season (i.e., end of October month), the water submerges the entire Beela area, the water-spread area representing its full capacity (Figure 3). The agricultural patta lands belonging to individual farmers are spread out up to the periphery of the Beela.



Figure 3. Beela wetland filled with water to its full capacity

Agriculture is the main occupation of the people in these villages, and farming depends majorly on the irrigation water supplied from Beela through the traditional gravity irrigation system practiced by local farmers for generations. The Batti is the local name for 'irrigation channel', which is the prime component in this irrigation system. A number of such Batti channels originate all around the periphery of the Beela. Thus, the local nomenclature Beela-Batti irrigation system emerged represent this traditional irrigation system in its totality.

The agricultural lands that are very close to the periphery of the Beela are low-lands where mostly water-intensive paddy crop is grown. Slightly away from the Beela are the middle-lands where vegetables are grown throughout the year. There is also the practice of coconut, areca nut and cashew farming in the lands located middle and higher lands. The soil type, irrigation water availability and the family labour availability decide the crops sown by the farmers across these lands.

The land holding of the majority of the farmers in this area is very small, varying from 0.1 acre to 1.0 acre, and fragmented too. It is common to find a farmer holding tiny pieces of land located at different locations in a village. The agriculture is mostly traditional, using the family labour and devoid of machines due to the smaller land holdings.

Apart from supporting the traditional subsistence farming around, the Beela also supports fishing activity and livelihoods of fishermen community (locally known as Jaalarulu). These fishermen from nearby villages engage in daily fishing activity for sale in local markets. In addition, households from different villages catch fish seasonally for their consumption or to sell smaller quantities in local markets.

3.1 The making of Batti irrigation channels

For many generations, farmers living around the Beela developed deep understanding of seasonal rise and fall in water levels in the Pedda Beela. They dug irrigation channels from the central portion of Pedda Beela towards their agricultural lands. This central area holds maximum water depth during both the monsoon season and dry periods. These channels, locally known as Battis, extend radially from the centre of wetland toward the surrounding agricultural lands (Fig.4).



Figure 4. A typical Batti channel carrying water to lands

These Batti channels generally measure about 1.5 to 2 m in width and 1 to 1.5 meters in depth. Their length varies from half a kilo meter to nearly three kilo meters. The channels are carefully aligned along gentle slopes to allow water to flow naturally by gravity from the wetland towards the farmlands without the need for mechanical pumping.

At the end of each Batti channel, farmers constructed dug-out masonry-lined wells or circular pits. These wells typically measure 2-4 m in diameter and 6-8 m in depth. The pits are comparatively much smaller in diameter and depth. The pit or well receives water from the channels, creates sufficient suction depth and makes it convenient for lifting of water for irrigation to surrounding lands (Fig.5).

Since the channels are connected with the Beela, the seasonal rise and fall of water is also reflected in the water stored in them. While a well at the end of the channel will be full to its brim when the Beela is full of water, the water level recedes in the well as the water in the Beela falls. Thus, there is a two-way flow and interaction taking place between the two of them.



Figure 5. Typical pit at the end of a Batti channel



Figure 6. Dry batti channel with weed growth

In the Beela-Batti system, there are a number of such Batti channels originating radially all around the periphery of the Beela, mainly on the northern and southern sides where large tracks of agricultural lands exist. Since the water in wetland also carries fine sand and silt particles, the channels get silted up over a period of time. Further, the earthen channels get disfigured and obstructed by the collapse of loose soil from the side slopes and growth of weeds (Fig.6). Therefore, regular maintenance of these channels by removing silt deposits and weeds is important for their effective functioning.

3.2 Lifting and use of water from the Batti channels

During the early years of the Batti system, farmers lifted water from collector wells at the end of the channels using traditional wooden devices known as tenda (Fig.7). A tenda is made of a bamboo or wooden pole of diameter 3-4 inches and length 5-7 m (15-22 ft). The pole is pivoted at 1.0-1.5 m (3-5 ft) from its thicker end, and a stone is tied to its end as a counterbalance. A bucket is tied to the thinner end. The farmer lowers the bucket into the well, fills it with water and easily lifts it with much less manual effort due to the counterweight provided at the other end. The lifted water is emptied into an open channel, which carries it to the crops for meeting irrigation needs.



Figure 7. A traditional tenda in operation by a farmer

With the advent of energy-driven pump-sets, farmers started using electricity or diesel-powered pump-sets for lifting water from the Batti channels. The electric pump-sets require supply of electricity through a network of distribution lines. Though the houses in the surrounding village are electrified, the electricity supply network is not widely expanded to agricultural lands in the area. Therefore, the majority of farmers use diesel-powered pump-sets to lift water from the Batti channels. These pumps are installed closer to the pits or wells at the end of channels and are operated whenever irrigation water is required. These energized pump-sets have taken over the traditional tenda, rendering them obsolete.

Typically, farmers use diesel pump-sets of 5-10 horsepower (HP) capacity. There are cases of individual farmers owning and using smaller pump-sets as well as a group of farmers collectively using a larger pump-set for lifting irrigation water. These pump-sets lift water from a depth of approximately 6 m and

convey it to agricultural fields through flexible pipes. Since electricity supply to agriculture is provided by the state government free of cost, farmers who have access to electricity for pumping do not pay any money. But, operating a diesel-powered pump-set require approximately one litre of diesel per hour, costing the farmer nearly Rs.100 per hour. A paddy crop in one acre of land requires approximately 3–4 hours of water application in a week time. Due to these higher costs involved in irrigating crops using diesel pump-sets, farmers lift and use water from Batti channels judiciously as a supplemental source to monsoon rains.

3.3 Crop pattern and productivity of agricultural lands in Beela-Batti system

During the Rabi season (winter months from October to March), almost all land irrigated by the Batti system is used for paddy cultivation. Moderate day temperatures ranging from 26 °C to 30 °C favour growth of short duration paddy varieties in these lands. The Beela-Batti irrigation system ensures a steady availability of irrigation water throughout this crop season.

Part of the rice from the paddy crop is partly retained by the farmers for their family consumption and the rest is sold either in the local markets or to the Government. The Civil Supplies Department of Government of Andhra Pradesh procures harvested paddy at a fixed minimum support price (MSP), ensuring guaranteed buy-back and income for farming households. This market intervention by the Government ensures that the market price does not fall below the MSP defined by it for a particular crop season. During the paddy crop period, peak irrigation demand occurs during December and January months. The Beela-Batti farmers groups manage water pumping and distribution by following rotational schedules, ensuring that every farm land receives necessary water at the right time.

During the Kharif (or monsoon season) from June to October, most Batti-irrigated lands, especially mid and high lands, are used for cultivating vegetables and fruits, such as, tomato, brinjal, chilli, okra, cucumber, bitter guard, ivy guard, watermelon, musk melon, and papaya. Tomato is grown using staking method² using bamboo poles. Vine crops like bitter guard are grown on traditional trellis structures made using bamboo poles and sticks (Fig.8). Sometimes, mixed vine crops are grown on the same trellis structures. These crops benefit from both rainfall and supplemental irrigation from Beela. The harvest is sold in the nearby markets for remunerative prices.

Farmers cultivate Paddy in Kharif season too, especially in low lands where the soil type and moisture conditions favour Paddy. The crop residues from vegetable and other crops during Kharif season enrich the soil for subsequent Paddy cultivation in Rabi season. Farmers access seeds and inputs through the Agriculture Department of the State Government. Also, some farmers preserve Paddy seeds for the next crop season. Perennial crops, like Ivy Guard, grow most of the year. End of its life cycle, farmers collect and preserve the roots for replanting in the same trellis structures.

During the summer months from April to June, the water in the Beela wetland recedes and exposes its bed partially. The dried bed soil in the Beela is enriched with nutrients and organic carbon due to the deposition of silt carried by water and decay of plant organic matter. This nutrient-rich soil from the wetland is taken out and applied in the farm lands to improve the soil structure, moisture retention capacity and to augment natural nutrients in the soil (Fig.9, Fig.10 & Fig.11). At the subsequent ploughing of soil, the applied Beela bed soil mixes well with the topsoil of land. This is a traditional practice among the farmers in the area for many generations. Farmers far away from the Beela also come to remove and carry the dried soil from its bed area for application in their farm lands as an organic fertilizer. Earlier, this process used to involve manual labour in removal of soil and loading on bullock carts. With the availability earth moving machines and tractors, the Beela soil removal and application in agricultural lands have become easier and quicker.

² Staking method involves installing rows of vertical bamboo poles, with equal spacing between poles. Threads or wires are tied horizontally connecting all the poles in a row. The Tomato plants are tied to these threads or wires and supported to grow vertically.



Figure 8. Bitter guard grown on a trellis structure

Such periodic removal of accumulated bed soil also helps to retain the storage capacity of the Beela. However, the communities around the Beela keep a check on the indiscriminate extraction and use of this soil for commercial purposes by outsiders. This traditional practice symbolizes the indigenous agricultural knowledge that integrates wetland conservation into sustainable farming practice.



Figure 9. The soil from the dry bed of Beela



Figure 10. The soil transported to agricultural lands



Figure 11. The Beela bed soil applied in the agricultural land

3.4 Collective management of Batti channels by farmers

The water withdrawal from the wells, its distribution to the irrigated land and the maintenance of the Batti channels are all done collectively by the farmers themselves. The infrastructure of wetland, channels, and wells that form the physical component of this irrigation system is braided by a well-defined farmers management system. Thus, it is appropriate to use the nomenclature 'Beela-Batti traditional irrigation system' to refer to the integral of these two components.

Typically, a group of 3–10 farmers own, manage and share water from a Batti channel. The land area irrigated from each Batti could be between 10–15 acres. Such groups of farmers' access water and manage its distribution among themselves. They evolved a shared-understanding on how to allocate water among themselves, and they collectively maintain the infrastructure (channel, well, and pumping

systems). They sit together, discuss the maintenance works to be done and execute them in close coordination. The costs of such repairs and maintenance are shared among themselves. When they together operate one pump-set for lifting water, they also share the costs of diesel and repairs to the pump-sets, if any.

All the landowners and leaseholders who access water from a channel form a 'Beela-Batti group'. The right to access water is integral to the land ownership. When a land is hereditarily transferred to the kin of a farmer or sold to another farmer, the customary water rights also get transferred to the new landowner.

It was found through physical verification and analysis of satellite imagery, that there are 46 channels are physically in good shape and in functional condition. 18 are dysfunctional and completely filled-up with silt. All these 64 channels together run for a length of 38 kilo meters. Approximately a gross area of 800 acres is under irrigation from these channels during Kharif and Rabi seasons every year.

4. Ecological functions and services of Beela Wetland

The Beela wetland represents one of the most ecologically significant freshwater ecosystems in the northern coastal region of Andhra Pradesh. Although widely recognized for supporting irrigation and fisheries, its ecological importance extends far beyond the provision of water resources. The wetland functions as an integrated ecological system where vegetation, wildlife, hydrology, soil, and human communities interact continuously to sustain biodiversity and ecosystem productivity.

Wetland vegetation constitutes one of the most fundamental ecological components of the Beela ecosystem. Grasses occupy extensive areas along the margins of the Beela where fluctuating water levels provide favourable conditions for growth. Species such as pampas grass form dense stands characterized by tall flowering plumes that provide shelter for birds, insects, amphibians, and small mammals. Reeds and sedges dominate shallow water areas where their extensive root systems stabilize saturated soils, reduce shoreline erosion, and trap suspended sediments transported by surface runoff. These vegetation belts also function as natural biofilters by absorbing excess nutrients, thereby improving water quality before runoff reaches deeper sections of the wetland.

Wetland vegetation plays a significant role in maintaining ecological stability through nutrient cycling and groundwater recharge. During the monsoon season, dense vegetation slows surface runoff, allowing greater infiltration into the soil and reducing soil erosion. Organic matter produced from decomposing leaves and stems enriches wetland sediments, enhances soil fertility, and supports microbial communities responsible for nutrient transformation.

Further, the Beela wetland serves as one of the most important bird habitats along the northern coast of Andhra Pradesh. Its extensive freshwater marshes and shallow water bodies provide ideal conditions for resident as well as migratory bird species. Field investigations and biodiversity assessments have recorded approximately 125 bird species in and around the Beela wetland, representing nearly three-fourths of the bird diversity documented from the Srikakulam district. The wetland supports a rich assemblage of waterbirds, including herons, ducks, waders, and kingfishers, in addition to numerous terrestrial birds inhabiting the surrounding grasslands and agricultural landscapes. During the migratory season extending from September to February, thousands of birds arrive from northern and Central Asia to utilize the wetland as a wintering habitat. The availability of abundant food resources, safe nesting sites, and relatively undisturbed resting areas makes the Beela ecosystem an important stopover along migratory flyways.

The ecological importance of the Beela wetland extends beyond its aquatic habitats to include a diverse assemblage of mammals, reptiles, amphibians, and invertebrates that occupy different ecological niches throughout the ecosystem. The combination of permanent water bodies, dense grasslands, marsh vegetation, elevated land patches, and adjacent agricultural fields creates favourable conditions for numerous wildlife species. Together, these organisms contribute to ecological stability by regulating food webs, maintaining nutrient cycles, and supporting natural ecosystem processes. Among the

mammalian fauna, foxes, wild boars, rodents, bats, and small carnivores are commonly associated with the wetland landscape. The coexistence of diverse wildlife within the Beela wetland reflects the ecological health of the ecosystem. Local communities traditionally avoid unnecessary disturbance to wildlife except where human safety is concerned, contributing to the continued persistence of many species.

The Beela wetland supports a productive freshwater fishery that constitutes both an important ecological component and a significant source of livelihood for local communities. Surveys conducted in the wetland have documented at least thirty-seven fish species, reflecting the ecological productivity of this freshwater ecosystem and its importance in sustaining aquatic biodiversity. Through feeding, excretion, and decomposition, fish facilitate nutrient cycling by converting organic matter into biologically available nutrients. These nutrients become incorporated into wetland sediments and are subsequently redistributed through seasonal water movement, thereby enhancing soil fertility in adjacent agricultural fields. Fishing forms a primary livelihood for the Jaalarlu fishing community and provides supplementary income for numerous farming households. In addition to supporting household nutrition through protein-rich food, fisheries contribute substantially to the local rural economy.

5. Groundwater recharge and salinity control by Beela Wetland

The hydrogeological setting of the Beela wetland is fundamental to understanding its role in sustaining groundwater resources and regulating salinity, which ultimately sustains agriculture in the coastal areas of Sompeta region. The Beela wetland forms part of an interconnected hydrological system comprising the Mahendratana river, seasonal storm water channels, shallow aquifers, agricultural lands, and the coastal plain adjoining the Bay of Bengal. The continuous interaction between surface water and groundwater enables the wetland to function as a natural recharge zone, providing freshwater to surrounding villages while maintaining the ecological stability of the landscape.

Geologically, the Sompeta coastal region consists predominantly of unconsolidated alluvial and coastal sediments deposited over thousands of years by riverine and marine processes. These sediments comprise alternating layers of sand, silt, clay, and gravel, which together form productive shallow aquifers. Sandy deposits possess relatively high permeability and permit rapid infiltration of surface water, whereas clay-rich layers retard vertical movement and temporarily retain groundwater within the subsurface. This combination of permeable and semi-permeable strata creates favourable conditions for shallow groundwater storage and availability in wells, ponds and other shallow water extraction structures (Fig.12 & Fig.13). Consequently, rainfall and wetland water infiltrate into the underlying aquifers where they are stored and later extracted through shallow wells for domestic and agricultural purposes.



Figure 12. A shallow well full of water near Beela



Figure 13. A seepage pond in the vicinity of Beela

The groundwater system surrounding the Beela wetland is predominantly composed of unconfined or shallow aquifers that are directly influenced by seasonal rainfall and wetland water levels. Unlike confined aquifers that are isolated beneath impermeable geological formations, unconfined aquifers respond rapidly to variations in recharge and groundwater abstraction. During the monsoon season, groundwater levels rise as infiltration from the wetland and surrounding catchment increases, whereas groundwater levels decline gradually during the dry season. Nevertheless, the presence of the Beela wetland significantly moderates these seasonal fluctuations by providing continuous recharge through seepage, thereby ensuring that groundwater remains available for longer periods than would otherwise be possible. The slow subsurface movement supplies water to dug wells, shallow tube wells, and seepage ponds. Such hydraulic connectivity explains why groundwater resources in villages surrounding the Beela often remain more reliable than those in comparable coastal areas lacking large freshwater wetlands. Thus, even in absence of seasonal monsoon rainfall in the area, farmers are able to cultivate crops using water available in the wells and ponds.

The proximity of the Bay of Bengal further enhances the importance of the Beela wetland from a hydrogeological perspective. Coastal aquifers are inherently vulnerable to seawater intrusion because freshwater and saline groundwater exist in dynamic equilibrium beneath the coastal plain. Excessive groundwater abstraction can reduce freshwater pressure within the aquifer, allowing saline water to progress inland. Continuous recharge from the Beela wetland maintains groundwater levels and contributes to preserving the freshwater hydraulic head that opposes saline intrusion. Consequently, the hydrogeological functioning of the wetland supports not only groundwater availability but also groundwater quality, thereby protecting drinking water sources and agricultural lands from salinity-related degradation.

6. Conclusion

The Beela-Batti system is a traditional, man-made irrigation system developed by local farming communities around the Beela wetland. The Batti channels, unlike the natural streams and seasonal rivulets, are artificially dug, maintained, and managed by groups of farmers for irrigation purpose. Also, they allow two-way water flow and facilitate distribution of water by lifting at their far end. The Batti channels convey the water from the depths of the Beela using natural slope and gravity flow without the need for external energy. Since the water almost reaches the farm lands by gravity, there is a substantial saving of conveyance costs for the farmers. This decentralized irrigation system allows equitable access

of copious Beela water for all the farmers across the villages. Also, due to the simplicity of the system, farmers could easily operate and maintain the system by themselves.

All the agricultural lands around Beela receive irrigation water through this system. After irrigating the fields, excess water flows back into the wetland through natural drains, forming a continuous cycle that sustains both agriculture and the wetland throughout the year. This close interdependence highlights the strong relationship between farming practices and wetland ecology. Through this system, Beela's natural water storage is transformed into a dependable irrigation network that supports cultivation of staple food crops, such as, paddy, vegetables etc. throughout the year. The continued use of the Batti system over the generations demonstrates not only its relevance to the local agriculture but also the skills of local farmers in managing them in a sustainable and efficient manner.

The placement and alignment of Batti channels reflect careful observation of the wetland's water depth and the gradient of its bed. Channels originate from the deeper areas of the Beela, and terminate near agricultural lands beyond the periphery of wetland. Earlier days, farmers used manual digging method and carried the dug-out soil on head loads for dumping on both the sides of these channels. The periodic silt removal was also done by farmers together as a group. However, availability of earth moving machines has turned this easier. Farmers started engaging machines for removing weeds and silt in these channels. The removal of silt deposits is a meticulous job for ensuring smooth flow of water towards its far end. Any deviation by less or excess removal of bed soil may severely affect the water flow. Locally available laterite stone and lime mortar were used for well construction, creating durable structures capable of withstanding long-term use and seasonal flooding. Thus, the local farmers sustained the Beela-Batti irrigation system without any external expertise and financial support.

The ecological integrity of the Beela wetland is largely governed by its hydrological regime. Seasonal inflows from rainfall and the Mahendratana River replenish freshwater storage, while gradual discharge through groundwater recharge and surface outflows maintains environmental stability throughout the year. These hydrological processes regulate nutrient cycling, improve water quality, sustain aquatic biodiversity, and provide reliable freshwater for agriculture and domestic use. Consequently, the wetland serves not only as an ecological asset but also as a critical component of the socio-economic landscape of Sompeta area in Andhra Pradesh.

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NANCIENT, YET STILL FUNCTIONING IRRIGATION SYSTEMS OF THE ZARAFSHAN RIVER BASIN: PRESERVING IRRIGATION HERITAGE THROUGH SUSTAINABLE REGIONAL DEVELOPMENT

LES ANCIENS SYSTÈMES D'IRRIGATION, MAIS TOUJOURS FONCTIONNELS, DU BASSIN DU FLEUVE ZARAFSHAN: PRÉSERVER LE PATRIMOINE D'IRRIGATION PAR LE BIAIS D'UN DÉVELOPPEMENT RÉGIONAL DURABLE

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Abstract

The Zarafshan River is among the oldest continuously utilized river systems in Central Asia. For more than two millennia it has sustained agricultural production, supported the emergence of major civilizations, and facilitated cultural exchange along the Great Silk Road. Three ancient canals—the Dargom, Eski Angor, and Eski Tuyatortar—remain operational today and continue to irrigate approximately 165,000 ha of agricultural land while preserving an outstanding engineering legacy dating from the fourth century BC to the early centuries AD.

This paper examines the historical evolution, engineering characteristics, and present-day significance of these canals. It further explores opportunities to transform them into integrated heritage corridors combining irrigation, environmental restoration, tourism, recreation, and regional economic development. Drawing upon recent infrastructure and urban development initiatives in Uzbekistan, the paper proposes a holistic approach in which functioning irrigation systems become catalysts for sustainable development without compromising their primary irrigation function or historical authenticity. The study demonstrates that ancient irrigation structures can continue serving contemporary society while preserving their outstanding universal value for future generations.

Résumé

Le fleuve Zarafshan compte parmi les plus anciens systèmes fluviaux exploités sans interruption en Asie centrale. Depuis plus de deux millénaires, il soutient la production agricole, favorise l'émergence de grandes civilisations et facilite les échanges culturels le long de la Route de la Soie. Trois anciens canaux – le Dargom, l'Eski Angor et l'Eski Tuyatortar – sont toujours en service et continuent d'irriguer environ 165 000 hectares de terres agricoles, tout en préservant un patrimoine d'ingénierie exceptionnel datant du IV^e siècle avant J.-C. aux premiers siècles de notre ère.

Cet article examine l'évolution historique, les caractéristiques techniques et l'importance actuelle de ces canaux. Il explore également les possibilités de les transformer en corridors patrimoniaux intégrés, combinant irrigation, restauration environnementale, tourisme, loisirs et développement économique régional. S'appuyant sur des initiatives récentes en matière d'infrastructures et d'aménagement urbain en Ouzbékistan, l'article propose une approche holistique dans laquelle les systèmes d'irrigation fonctionnels deviennent des catalyseurs de développement durable, sans compromettre leur fonction première d'irrigation ni leur authenticité historique.

L'étude démontre que les anciennes structures d'irrigation peuvent continuer à servir la société contemporaine tout en préservant leur valeur universelle exceptionnelle pour les générations futures.

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Keywords: Zarafshan River, irrigation heritage, World Heritage Irrigation Structures, Silk Road, sustainable development, Uzbekistan, ancient canals

1. Introduction

Water has shaped the civilizations of Central Asia more profoundly than any other natural resource. Among the region's river systems, the Zarafshan River occupies a unique position because it has continuously supported human settlements, agriculture, trade, and cultural development for more than two thousand years. The name Zarafshan derives from Persian, meaning "the spreader of gold," reflecting both the alluvial gold historically transported by the river and the prosperity generated through its irrigation waters. Known to ancient Greek geographers as the Polytimetus, the river became one of the principal arteries supporting the flourishing oasis civilizations of Samarkand, Bukhara and surrounding regions.

Unlike many archaeological hydraulic works that survive only as ruins, several irrigation canals constructed more than two thousand years ago remain operational today. These canals continue to deliver irrigation water using the same fundamental hydraulic principles employed by their original builders. Their continued operation demonstrates remarkable engineering durability and provides an exceptional example of sustainable infrastructure whose useful life extends across multiple civilizations, political systems and technological eras.

This paper investigates three of the oldest functioning canals of the Zarafshan Basin, namely Dargom Canal, Eski Angor Canal, and Eski Tuyatortar Canal. Together these canals illustrate how ancient irrigation engineering continues to contribute to modern agricultural production while offering significant opportunities for heritage conservation and sustainable regional development.

2. From Ancient Hydraulic Knowledge to Modern Water Management

Historical development of irrigation in the Zarafshan Basin: Archaeological evidence indicates that organized irrigation developed within the Zarafshan Valley several centuries before the Common Era. Early communities recognized that stable agricultural production required controlled diversion of river flows onto fertile alluvial plains. Successive civilizations—including Achaemenid, Hellenistic, Kushan, Sogdian, Timurid and later Uzbek states—expanded and maintained increasingly sophisticated canal systems. Irrigation enabled permanent settlements to flourish despite the semi-arid climate.

The prosperity of Samarkand, one of the world's oldest continuously inhabited cities, depended directly upon these irrigation networks. Throughout history the canals experienced repeated destruction due to military invasions, river floods, sediment deposition, political instability, and abandonment during conflicts. Remarkably, each period of decline was followed by reconstruction, illustrating the strategic importance of irrigation to regional survival.

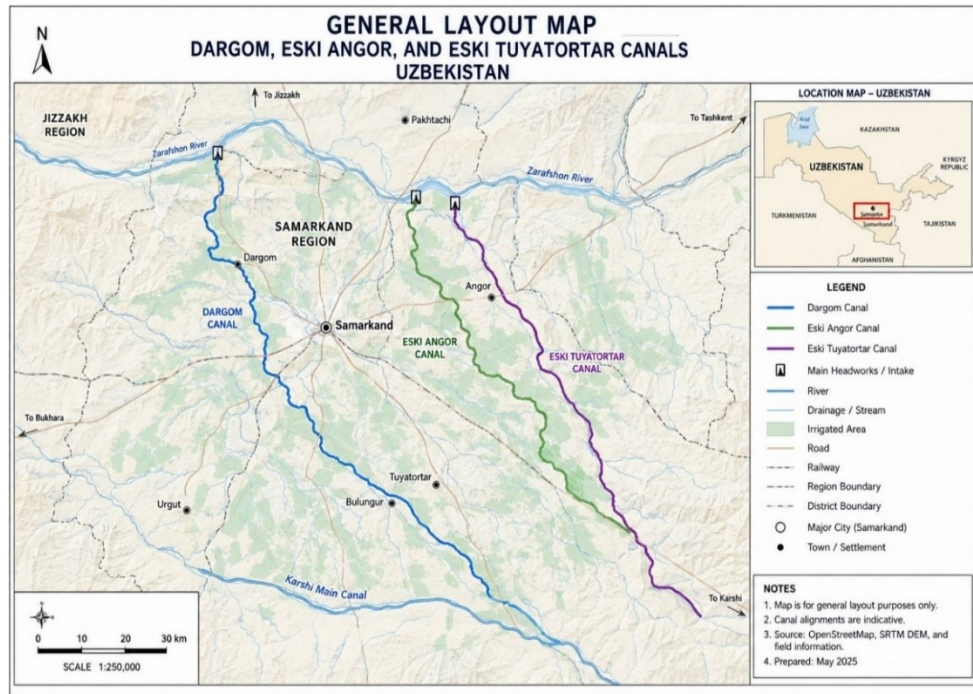
Hydrological characteristics of the Zarafshan River: The Zarafshan River is one of Central Asia's oldest transboundary rivers and has sustained irrigated agriculture for more than two millennia. Originating from the glaciers of the Turkestan and Zarafshan mountain ranges in Tajikistan at elevations exceeding 3,000 m, the river flows approximately 877 km before dissipating within the arid plains of Uzbekistan. Unlike many major rivers of Central Asia, the Zarafshan no longer reaches the Amu Darya because virtually all of its flow is diverted for irrigation.

The hydrological regime is dominated by snow and glacier melt. Annual runoff generally begins increasing during April, reaches maximum discharge between June and August, and gradually decreases during autumn. Winter flows remain comparatively low. The river supplies irrigation water to approximately one million hectares of agricultural land, making it one of the most intensively utilized river systems in Central Asia.

Water Availability: The coincidence between maximum river discharge and peak irrigation demand has historically contributed to the sustainability of the ancient canal system. Water availability varies considerably throughout the year owing to seasonal snowmelt and glacier contributions. Typical seasonal characteristics are:

Season	Hydrological Condition	Irrigation Implication
Winter	Low flow	Minimal irrigation demand
Spring	Increasing discharge	Canal filling and land preparation
Summer	Peak discharge	Maximum irrigation supply
Autumn	Declining discharge	End of irrigation season

Ancient canal diversion system: The ancient inhabitants of Sogdiana developed an ingenious gravity-fed irrigation network by constructing diversion structures along the Zarafshan River. Water was conveyed through a hierarchy of main canals, secondary canals, tertiary canals and field channels without mechanical pumping. The principal historic canals include: Dargom Canal, Bulungur Canal, Tuyatortar Canal, Eski Angar Canal, and Mirzaaryk Canal. These canals continue to form the backbone of the modern irrigation system serving the Samarkand oasis. The hydraulic concept developed over two thousand years ago remains fundamentally unchanged, demonstrating exceptional engineering foresight and long-term resilience.



Dargom Canal is believed to have originated during the fourth to fifth centuries BC and represents one of Central Asia's earliest large-scale irrigation works. Historical records indicate that Claudius Ptolemy depicted the canal on his world map, illustrating its significance even during antiquity. The canal repeatedly suffered damage from flooding and military invasions, including destruction during the Mongol conquest in 1220. Reconstruction efforts throughout subsequent centuries culminated in major rehabilitation during the early Soviet period. Today the canal remains a principal irrigation artery supplying agricultural land throughout the Samarkand region.

Eski Angor Canal constructed during the first century BC, has significantly expanded irrigation toward southern agricultural lands. Although periodically abandoned due to warfare and changing political circumstances, the canal was comprehensively reconstructed in 1955. Its continued functionality illustrates the adaptability of ancient hydraulic alignments to modern irrigation requirements.

Eski Tuyatortar Canal was originally constructed during the early centuries AD. Following repeated damage throughout regional conflicts, it underwent major reconstruction during the sixteenth century before receiving further rehabilitation during the Soviet period. Recognition of its exceptional historical significance culminated in its selection for the World Heritage Irrigation Structure (WHIS) Award 2025.

Despite their antiquity, the three canals remain critical components of Uzbekistan's irrigation infrastructure. Collectively they extend nearly 400 km and divert approximately 220 m³/s from the Zarafshan River. Their command area exceeds 165,000 hectares distributed across Samarkand, Kashkadarya, and Jizzakh regions. The canals support production of wheat, cotton, fruits, vegetables, horticultural crops, and fodder crops. They also provide water for rural settlements, ecological habitats and groundwater recharge.

Modern engineering assessment: From a hydraulic engineering perspective, the ancient canals demonstrate several characteristics consistent with modern sustainable irrigation design including efficient gravity conveyance, low energy requirements, adaptable water distribution, flexibility for expansion, compatibility with rehabilitation, integration with natural topography, and sustainable hydraulic gradients. Modern rehabilitation has focused primarily on improving hydraulic efficiency through canal lining, upgraded control structures, improved measurement facilities and better operational management rather than altering the original canal alignments.

Hydraulic characteristics: The ancient canals were designed according to remarkably sound hydraulic principles. Typical engineering characteristics include:

Parameter	Typical Characteristics	Parameter	Typical Characteristics
Flow regime	Gravity flow	Longitudinal slope	Mild uniform gradient
Canal type	Earthen (partly lined today)	Sediment transport	Natural self-cleansing where velocities are maintained
Cross section	Trapezoidal	Flow condition	Subcritical

Hydraulic performance: The longevity of these canals reflects several favorable hydraulic characteristics.

Gravity conveyance: The canals utilize natural topographic gradients, eliminating energy requirements for water conveyance. Stable flow: The relatively gentle longitudinal slopes produce predominantly subcritical flow, minimizing erosion while maintaining adequate conveyance capacity. Water distribution: Numerous division structures allow proportional allocation of water among irrigation districts and agricultural lands. Hydraulic efficiency: Despite their antiquity, the canals continue to operate efficiently following periodic rehabilitation and maintenance.

Hydrological sustainability: The long-term sustainability of the Zarafshan irrigation system depends upon balancing water diversion with available river discharge. The principal challenges include increasing upstream abstractions, glacier retreat, reduced snow accumulation, climate variability, sedimentation, and increasing irrigation demand. Nevertheless, the resilience demonstrated over more than two millennia indicates that the original designers successfully matched hydraulic capacity with the natural hydrological regime.

Engineering heritage of the ancient canals: The hydraulic and hydrological assessment indicates that the ancient irrigation canals of the Zarafshan River Basin represent one of the world's most enduring examples of sustainable hydraulic engineering. The principal engineering significance of the Dargom, Eski Angor and Eski Tuyatortar canals is not simply their age, but the fact that their basic hydraulic alignments and functions have survived through successive historical periods and remain incorporated into contemporary irrigation systems. This continued operation illustrates how carefully selected diversion locations, gravity-based conveyance, appropriate channel gradients and regular maintenance have enabled reliable irrigation over more than two thousand years. The construction of large irrigation canals in the Zarafshan Basin required a sophisticated understanding of terrain, river behavior, gradients, soil conditions, water availability and agricultural requirements. In an environment where the difference in elevation along long canal reaches could be relatively small, achieving a stable hydraulic gradient was essential. Excessive slopes could cause erosion, whereas insufficient slopes could result in sediment deposition and loss of conveyance capacity. The ancient engineers therefore had to solve problems that remain fundamental to modern canal engineering including identification of suitable diversion points, establishment of stable longitudinal gradients, determination of canal dimensions, control of flow velocities, management of sediment, protection of banks against erosion, crossing of natural drainage channels, distribution of water among irrigation areas, and maintenance of hydraulic structures. The continued existence of these canals demonstrates that the original alignments were strongly adapted to the natural topography of the Zarafshan Valley.

Key engineering findings: Continued investment in modernization, combined with integrated basin water management and climate adaptation, will be essential to preserve this remarkable hydraulic heritage while meeting future agricultural water demands.

Cultural and historical importance: Beyond engineering achievements, these canals represent living cultural landscapes. For centuries they have shaped settlement patterns, agricultural traditions, local architecture, water governance, folklore, religious practices, and community identity. Unlike archaeological monuments that preserve static historical evidence, functioning canals continue performing their original purpose while simultaneously serving as heritage assets. This continuity significantly enhances their cultural value.

Evolution rather than replacement: An important characteristic of these canals is that they have not remained technologically unchanged. Their history represents a process of continuous adaptation. Ancient canals were constructed using the engineering knowledge and labor technologies available at the time. Subsequent civilizations repaired, and reconstructed them. Later rehabilitation programs introduced modern hydraulic structures, earthworks, lining, control gates and other components.

Consequently, today's canals should not be interpreted as completely unchanged archaeological artefacts. They are better understood as evolving hydraulic landscapes, in which ancient alignments and water-management traditions have been integrated with modern engineering. This distinction is important for heritage management. The objective should not necessarily be to freeze the canals in their historical state. Such an approach could conflict with their continuing irrigation function. Instead, conservation should seek to maintain the historic character and significant features of the system while permitting technically necessary modernization.

Hydraulic performance and modernization: Modernization may involve improvement of control structures, installation of flow measurement devices, automation of selected regulators, reduction of seepage where economically and environmentally justified, modernization of offtakes, introduction of remote monitoring, and improved water accounting. However, conventional modernization approaches can unintentionally destroy heritage values. Complete concrete lining, replacement of traditional structures, widening of historic alignments or removal of mature vegetation may improve certain engineering parameters while reducing cultural and ecological value. A heritage-sensitive modernization methodology is therefore required. Modernization of these canals needs to address two potentially competing objectives:

Preserving irrigation heritage, and improving hydraulic efficiency and operational reliability.

Hydraulic efficiency versus heritage value: Not every canal section requires the same engineering treatment. The canal system could be divided into three functional categories:

Canal section	Primary objective	Appropriate intervention
High heritage significance	Conservation	Minimum intervention and structural conservation
Irrigation-critical section	Hydraulic performance	Carefully designed rehabilitation
Urban/tourism section	Multifunctional use	Irrigation + recreation + landscape enhancement

This zonal approach would permit modern engineering techniques to be concentrated where they are most necessary while preserving representative historic sections.

Sediment management: Sedimentation represents one of the most important engineering challenges in the Zarafshan irrigation system. The Zarafshan carries substantial sediment loads derived from mountainous catchments, particularly during periods of high river discharge. Sediment entering irrigation canals progressively reduces their effective hydraulic cross-section and can cause reduced discharge capacity, increased water levels, local overtopping, reduced reliability of offtakes, uneven distribution of water, and increased maintenance requirements. Historically, canal managers addressed sediment deposition through annual desilting, maintenance of design slopes, periodic canal closure, community-based maintenance, and removal of vegetation and debris. These traditional maintenance practices have contributed significantly to the remarkable longevity of the irrigation network. Sediment management should therefore form part of both the irrigation modernization program and the heritage management strategy. Importantly, historical canal sections should not automatically be excavated to a modern standardized cross-section. Before major desilting works, historical profiles should be documented and their hydraulic significance evaluated.

Water measurement and digitalization: The heritage value of the canals does not prevent them from becoming technologically advanced. Modern water-management technologies could be introduced with minimal visual impact, including ultrasonic flow meters, automatic water-level sensors, remote telemetry, GIS-based canal asset registers, satellite-based monitoring, digital hydraulic models, and automated gates at strategically selected locations.

A digital twin of the Zarafshan irrigation heritage system could eventually integrate historical canal maps, current hydraulic characteristics, structures, water levels, agricultural demand, maintenance records and heritage assets which would provide a powerful tool for managing an irrigation network that is simultaneously an agricultural asset and a cultural landscape.

Climate resilience: Climate change increases the importance of modernizing the operational management of these historic systems. Future planning should consider increased temperature, changing river runoff patterns, drought frequency, extreme precipitation, flood events, increased irrigation demand, and evaporation losses. The objective should be to increase the resilience of the canals without compromising their historical identity. The ancient canals therefore provide an unusual opportunity: modern climate-resilient engineering can be applied to infrastructure whose fundamental hydraulic concept has already demonstrated exceptional long-term resilience.

3. Opportunities for Sustainable Regional Development

Recent national development initiatives demonstrate Uzbekistan's increasing commitment to integrating infrastructure, tourism and environmental enhancement. Examples include: the New Tashkent urban expansion, the Silk Road tourism complex in Samarkand, and restoration of historical public spaces in general, these projects illustrate how engineering infrastructure can simultaneously deliver economic, environmental and social benefits. Applying similar concepts to the ancient canals could establish integrated heritage corridors connecting agriculture, tourism, ecology and recreation. Potential interventions include:

Heritage conservation including preservation of historic hydraulic structures, interpretation centers, canal museums, and archaeological protection. Eco-tourism including cycling trails, walking routes, riverfront parks, observation platforms, and boating opportunities where appropriate. Environmental enhancement including wetland restoration, biodiversity corridors, native vegetation planting, and improved water quality monitoring. Community development including local handicraft markets, cultural festivals, traditional irrigation demonstrations, and educational programs. Agricultural innovation including efficient irrigation technologies, climate adaptation, precision agriculture, and water-saving practices.

Integrated development concept: Rather than viewing irrigation canals solely as water conveyance infrastructure, future planning should recognize them as multifunctional regional assets. An integrated development model would combine irrigation management, heritage conservation, tourism, environmental restoration, flood management, urban development, recreation, education, and climate resilience. Such an approach aligns with international principles promoting sustainable management of cultural landscapes while maintaining their original functions.

4. Silk Road Tourism Complex in Samarkand: A Model for Integrating Irrigation Heritage with Regional Development

The development of the Silk Road Samarkand tourism complex represents one of Uzbekistan's most ambitious investments in cultural tourism, urban regeneration, and landscape development. Conceived as a flagship project to diversify the regional economy and strengthen Samarkand's position as an international tourism destination, the complex demonstrates how large-scale infrastructure investments can successfully integrate cultural heritage, water engineering, environmental enhancement, and economic development.

Constructed on previously underutilized land east of the historic city, the project transformed an area characterized by sparse vegetation and limited economic activity into a multifunctional destination comprising hotels, conference facilities, recreational areas, cultural attractions, residential developments, public parks, and waterfront landscapes. Rather than functioning solely as a tourism facility, the complex has become an example of integrated territorial planning in which water infrastructure serves as the organizing element of urban development. Although the project is contemporary, many of its planning principles are directly applicable to the conservation and revitalization of Uzbekistan's ancient irrigation canals.

Water as the organizing element of development: Historically, cities along the Silk Road were established where reliable water resources supported agriculture, trade, and urban life. Samarkand itself owes its existence to the waters of the Zarafshan River and its extensive network of irrigation canals. The Silk Road Samarkand development consciously reintroduced water as the defining feature of the landscape. Instead of treating canals and reservoirs merely as hydraulic infrastructure, they were incorporated as multifunctional public assets providing visual identity, recreational opportunities, flood regulation, environmental enhancement, landscape cooling, biodiversity habitats, tourism attractions, and high-quality urban spaces.

Artificial lakes, landscaped canals, pedestrian promenades, and green corridors have become central components of the visitor experience while simultaneously performing hydraulic functions. This multifunctional approach reflects contemporary concepts of integrated water resources management and nature-based urban development. The project demonstrates that investments in water infrastructure can generate benefits extending far beyond irrigation or drainage, contributing to public health, climate resilience, tourism, and economic growth.

Engineering transformation of the landscape: Prior to development, much of the project area consisted of relatively undeveloped land with limited infrastructure. Through coordinated engineering works, the site was transformed using a combination of canal construction and rehabilitation; excavation of water bodies; stormwater management systems; groundwater regulation; landscape irrigation; road infrastructure; utilities; ecological restoration; and architectural development.

The resulting landscape illustrates how hydraulic engineering can provide the structural framework upon which diverse urban functions are organized. Rather than concealing water infrastructure, the project celebrates it as a defining landscape feature. This design philosophy closely resembles historical settlements of Central Asia, where irrigation canals simultaneously served agricultural, domestic, commercial, social, and environmental purposes. Economic benefits generated by water-based development: The Silk Road Samarkand complex has demonstrated that water-centered investments can become significant economic drivers. Benefits include expanded international, conference and business tourism; creation of thousands of direct and indirect jobs; increased property values; stimulation of private investment; support for local handicrafts and cultural industries; and increased municipal revenues. Importantly, these economic gains were achieved while enhancing environmental quality and public accessibility. This experience provides valuable lessons for future development initiatives associated with ancient irrigation canals.

Relevance to the ancient canals of the Zarafshan Basin: Unlike newly constructed urban waterways, the Dargom, Eski Angor, and Eski Tuyatortar canals already possess exceptional historical, engineering, and cultural significance. This unique combination of living heritage and operational infrastructure offers opportunities that exceed those available for newly created tourism developments. Instead of constructing entirely new attractions, regional development could capitalize upon existing cultural landscapes that have evolved over more than two millennia. The canals already provide authentic historical narratives, functioning hydraulic systems, traditional agricultural landscapes, mature vegetation, historic settlements, archaeological sites, cultural monuments, and ecological corridors. These characteristics form an ideal foundation for sustainable tourism development.

Establishing the Zarafshan Irrigation Heritage Corridor: Drawing upon the experience of the Silk Road Samarkand project, the three ancient canals could form the backbone of a regional Zarafshan Irrigation Heritage Corridor. Rather than viewing each canal as an isolated hydraulic structure, they could be managed as interconnected cultural landscapes extending from the upper reaches of the Zarafshan River through agricultural areas toward the downstream regions.

Such a corridor would integrate irrigation engineering, historical monuments, archaeological sites, Silk Road settlements, agricultural tourism, ecological conservation, cycling routes, walking trails, cultural festivals, and educational facilities. Visitors would experience not only historic cities but also the water systems that made those cities possible. This concept broadens the traditional interpretation of Silk Road tourism by recognizing irrigation infrastructure as an essential component of the region's civilization.

Potential tourism nodes along the canals: The canal corridors could be organized into a network of themed destinations linked by transportation and visitor services. Potential components include:

Historic hydraulic structures: Restored diversion weirs, head regulators, bridges, and canal crossings could be interpreted through visitor centers explaining ancient irrigation engineering. **Living agricultural landscapes:** Demonstration farms could showcase traditional irrigation techniques alongside modern water-saving technologies. **Canal waterfronts:** Selected urban sections could be landscaped with

pedestrian promenades, shaded parks, cafés, cultural performance spaces, bicycle lanes, and viewing platforms. Heritage villages: Communities located along the canals could promote traditional crafts, local cuisine, homestay tourism, cultural festivals, and agricultural experiences. Ecological parks: Riparian habitats could be restored to improve biodiversity while creating recreational opportunities for birdwatching and environmental education.

Linking the canals with existing tourism infrastructure: The success of the Silk Road Samarkand complex provides an opportunity to extend visitor experiences beyond the boundaries of the city. Currently, many international visitors remain concentrated within Samarkand's historic center and nearby attractions. The ancient canals could diversify tourism by creating thematic excursions focusing on ancient hydraulic engineering, irrigation heritage, Silk Road agriculture, rural landscapes, environmental conservation, and traditional water management.

Tourists attending conferences or staying within the Silk Road Samarkand complex could participate in day trips following sections of the Dargom Canal before continuing to the Eski Angor and Eski Tuyatortar systems. This would distribute tourism revenues more widely across rural communities while reducing visitor pressure on heavily visited historic monuments.

Environmental and climate benefits: The proposed heritage corridor would also contribute to environmental sustainability. Canal rehabilitation projects could incorporate riparian vegetation restoration, groundwater recharge, habitat creation, erosion control, urban cooling, carbon sequestration, improved water quality, and climate adaptation measures. These interventions align closely with contemporary principles of Nature-based Solutions and Integrated Water Resources Management. Rather than competing with irrigation objectives, environmental improvements would enhance long-term canal performance while increasing their attractiveness for tourism.

Institutional framework: Implementation would require close cooperation among multiple institutions, including the Ministry of Water Resources; the Ministry of Ecology, Environmental Protection and Climate Change; the Ministry of Culture; the Tourism Committee; regional and local governments; irrigation authorities; universities; local communities; and private investors. Such coordination mirrors the institutional collaboration that enabled successful implementation of the Silk Road Samarkand project.

A vision for living irrigation heritage: The experience of Silk Road Samarkand demonstrates that water infrastructure can become a catalyst for broad socioeconomic transformation when integrated with landscape design, cultural heritage, and environmental planning. Applying this philosophy to the Dargom, Eski Angor, and Eski Tuyatortar canals would not require altering their primary irrigation function. Instead, it would reveal and enhance the multiple values these canals already possess as living heritage. Unlike many historic hydraulic works that survive only as archaeological remains, these canals continue to convey water, sustain agricultural production, and support local communities. Their authenticity lies not only in their age but in their uninterrupted operation across more than two millennia. By linking the Silk Road Samarkand tourism complex with a broader Zarafshan Irrigation Heritage Corridor, Uzbekistan could create an internationally distinctive destination where visitors experience the complete story of the Silk Road—from monumental architecture and urban centers to the irrigation systems that made those achievements possible. Such an integrated approach would reinforce the country's cultural identity, diversify regional economies, support rural livelihoods, and ensure that these remarkable irrigation systems continue to serve both agriculture and society well into the future.

5. From Irrigation Canals to Development Corridors: Heritage Conservation Principles for Living Irrigation Structures

From monuments to living heritage: The Dargom, Eski Angor and Eski Tuyatortar canals differ fundamentally from conventional archaeological monuments. A historic building can potentially be conserved without continuing its original function. An irrigation canal cannot. Its identity is intrinsically connected with the movement of water and its relationship with agriculture and settlements. These canals should therefore be treated as living irrigation heritage. Their heritage significance derives from

several interconnected values like historical, technological, cultural, landscape, social, agricultural, ecological, and educational. Conservation should address all these dimensions rather than focusing exclusively on surviving masonry or archaeological remains.

Authenticity: Authenticity is particularly important for irrigation heritage. The fact that these canals continue to perform their original function is itself one of their most powerful heritage attributes. For these canals, authenticity can include:

Physical authenticity: Historic alignments, structures and construction materials. **Functional authenticity:** Continued use for irrigation. **Landscape authenticity:** Relationship between the canal, agricultural land, settlements and surrounding landscape. **Cultural authenticity:** Continuation of traditional water-management practices and community relationships.

Historical authenticity: Evidence of successive phases of development.

Conservation should not mean fossilization: A major conservation principle should be that preservation does not require technological stagnation. If a historic regulator becomes unsafe, it may be necessary to strengthen or reconstruct it. If a canal section repeatedly fails, rehabilitation may be unavoidable. If water losses threaten the sustainability of the irrigation system, selective lining may be justified. The appropriate question is therefore not: "Can modernization be avoided?" but rather: "How can modernization be undertaken while retaining the attributes that establish the heritage significance of the canal?" This principle should guide all future rehabilitation.

Documentation before intervention: Before rehabilitation, a comprehensive heritage inventory should be prepared to record canal alignment, historic structures, bridges, regulators, aqueducts, offtakes, archaeological remains, traditional settlements, historic vegetation, culturally significant locations, photographs, historical maps, and oral histories. Each heritage feature should receive a unique identification number and be incorporated into a GIS database which would create a Zarafshan Irrigation Heritage Register.

Classification of heritage significance: Not every element of a 400-km irrigation system will have identical heritage significance. A classification system could be established allowing investment decisions to be prioritized rationally:

- Grade I-Exceptional significance: Structures or canal sections with outstanding historical or technological value.
- Grade II-High significance: Historic components that contribute substantially to the character of the irrigation landscape.
- Grade III-Local significance: Features associated with traditional agriculture, community history or local identity.
- Grade IV-Functional infrastructure: Modern components with limited historical significance but important operational functions.

Minimum intervention and reversibility: Where a structure has high heritage significance, interventions should follow internationally recognized conservation principles such as minimum necessary intervention, compatibility of new materials, retention of original fabric, distinguishability of new construction, reversibility where practical, and detailed documentation. Modern additions should not create false historical interpretations. For example, a modern flow-monitoring device may be installed discreetly without reconstructing a historic structure inaccurately.

Community participation: The heritage of the canals is not confined to physical infrastructure. Generations of farmers and water managers have developed knowledge concerning irrigation scheduling, canal maintenance, flood response, water allocation, and traditional agricultural practices.

This intangible heritage should be documented alongside the physical structures. Local communities should therefore participate in heritage planning through oral-history programs, community mapping, school programmes, local museums, traditional irrigation demonstrations, and cultural events. This would ensure that heritage conservation remains connected to the people who continue to use and maintain the canals.

Heritage impact assessment: Major infrastructure projects intersecting the canals should be subject to a Heritage Impact Assessment before construction. This should apply to roads, railways, pipelines, urban expansion, industrial development, canal modernization, and tourism facilities. Alternative designs should be considered where a project could substantially affect a significant canal section or historic structure with the objective to avoid unnecessary fragmentation of the historic irrigation landscape.

6. From Ancient Irrigation to Future Heritage: Sustainable Regional Planning

The canal as a regional development axis: The traditional planning approach considers irrigation canals primarily as infrastructure serving agricultural land. For the Zarafshan Basin, a broader concept is possible. The Dargom, Eski Angor and Eski Tuyatortar canals can be viewed as regional development axes connecting water, agriculture, settlements, cultural heritage, tourism and ecological systems. Their combined length of approximately 400 km creates a potential regional network extending well beyond individual heritage sites. The proposed planning model can therefore be represented as creating a direct connection between irrigation infrastructure and regional socioeconomic development:

Zarafshan River → Ancient canals → Agricultural landscapes → Historic settlements → Cultural heritage → Ecological corridors → Tourism → Local economic development

The Zarafshan Irrigation Heritage Corridor: A long-term objective could be the establishment of a Zarafshan Irrigation Heritage Corridor which would not necessarily require the entire 400-km canal system to become a tourism facility. Instead, selected nodes and representative sections could be developed while the remainder continues operating primarily as irrigation infrastructure. The corridor could contain the following nodes creating a distributed tourism model rather than concentrating visitors in a single location:

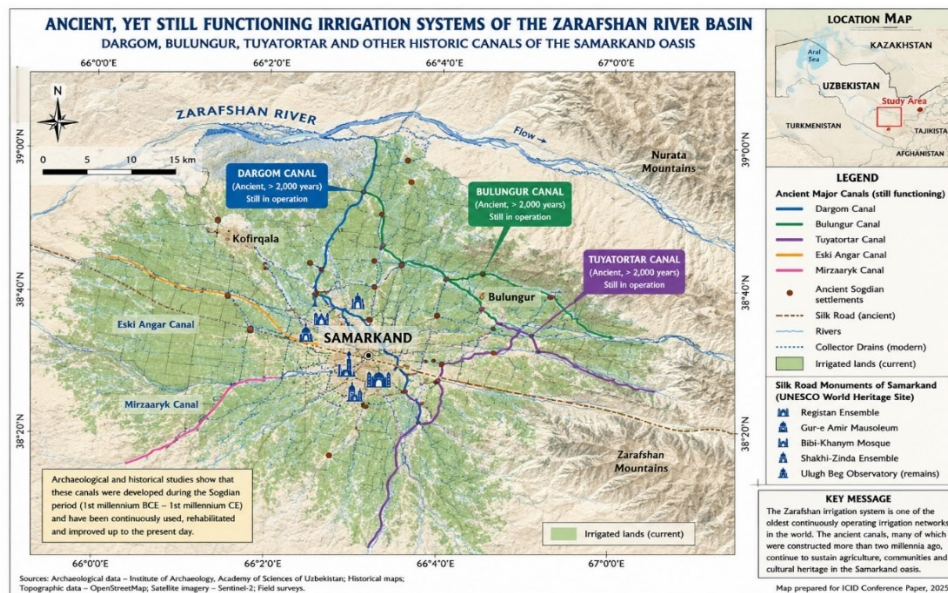
- Heritage nodes: Important historic structures.
- Tourism nodes: Visitor facilities and attractions.
- Agricultural nodes: Demonstration farms.
- Ecological nodes: Wetlands and biodiversity areas.
- Urban nodes: Canal-front public spaces.
- Community nodes: Villages and cultural centers.

Connecting Samarkand with rural areas: The Silk Road Samarkand complex provides an important starting point. Samarkand is already an internationally recognized tourism destination. The ancient canals can extend the visitor experience beyond the city's monuments. A visitor itinerary could, for example, connect: Samarkand historic center → Silk Road Samarkand → Dargom Canal → Traditional irrigation landscape → Historic hydraulic structure → Agricultural community → Eski Tuyatortar → Other Silk Road heritage destinations.

This would create a new tourism product centered on the water infrastructure that enabled the Silk Road civilization itself.

Avoiding mass-tourism impacts: Development should not transform the canals into conventional tourist attractions. Uncontrolled tourism could create litter, water pollution, bank erosion, traffic, disturbance of communities, and inappropriate commercial development. A sustainable planning model should therefore establish visitor-capacity limits and zoning. Sensitive areas should remain restricted, while appropriate locations could accommodate tourism facilities.

Green and blue infrastructure: The canal corridors could become components of a regional blue-green infrastructure network. The "blue" component would include canals, ponds, wetlands, drainage channels, and floodwater storage. The "green" component would include riparian vegetation, parks, agricultural landscapes, ecological corridors, and tree belts. Together they could provide flood attenuation, urban cooling, biodiversity, recreation, landscape improvement, and carbon sequestration. This is particularly relevant as Samarkand and surrounding settlements experience increasing urbanization.



Urbanization and protection of irrigation heritage: Rapid urban development represents one of the principal long-term risks to historic canals. New urban areas can fragment canal corridors through road construction, building development, utility crossings, canal relocation, pollution, and encroachment. Future master plans should therefore establish protected canal corridors. Within these corridors, development controls could regulate building setbacks, crossings, landscaping, wastewater discharge, access, and visual impacts. The objective would be to ensure that urban growth strengthens rather than destroys the relationship between the city and its historic water system.

Agriculture as part of the heritage landscape: Agriculture should remain a central component of the heritage concept. The canals cannot be separated from the irrigated landscapes they created. Future projects could establish demonstration areas showing traditional irrigation, modern drip irrigation, water-efficient farming, traditional crops, orchards, and local food production. This would allow visitors to understand that the prosperity of Samarkand and other Silk Road settlements was based not only on trade and architecture but also on sophisticated agricultural water management.

Economic development and local communities: A sustainable heritage corridor should generate tangible benefits for local residents. Potential opportunities include community-based tourism, homestays, restaurants, local food products, handicrafts, agricultural experiences, guiding services, maintenance employment, and cultural events. This creates an important conservation mechanism: Heritage generates income → Communities benefit → Communities support conservation → Heritage is maintained.

Governance and financing: A regional initiative would require an institutional structure capable of coordinating water management and heritage development. A potential governance framework could include a Zarafshan Irrigation Heritage Coordination Council involving water-management authorities, cultural heritage institutions, tourism authorities, environmental authorities, regional governments,

municipalities, agricultural organizations, academic institutions, local communities, and private investors. Financing could combine government infrastructure budgets, tourism investment, environmental programs, international development financing, heritage grants, private-sector investment, and public-private partnerships.

A long-term planning vision: The ultimate objective should not be simply to "restore ancient canals for tourism." It should be to create a living regional system in which irrigation, heritage, ecology and economic development reinforce one another. The three canals could become an international demonstration of how historic water infrastructure can contribute to contemporary development without losing its cultural identity. The experience of the Silk Road Samarkand complex provides evidence that carefully planned water-based landscapes can become powerful economic and social assets. The ancient canals offer something even more valuable: they provide an authentic historical connection between water, agriculture and civilization that has survived for more than two thousand years. The three themes; irrigation engineering, heritage conservation and sustainable regional planning should ultimately be treated as one integrated system.

The Dargom, Eski Angor and Eski Tuyatortar canals should therefore be presented not as isolated ancient structures, but as components of a continuous socio-hydraulic system. This perspective could become one of the central arguments of the conference paper: the greatest heritage value of the Zarafshan canals lies precisely in the fact that they are ancient systems that have not ceased to function. Their conservation should consequently aim not at preserving obsolete infrastructure, but at ensuring that an exceptionally long-lived irrigation civilization can continue to evolve while retaining its historical identity.

Dimension	Historical function	Modern objective	Heritage contribution
Irrigation engineering	Convey water	Improve efficiency and resilience	Preserve hydraulic knowledge
Canal structures	Control and distribute water	Ensure safe operation	Preserve technological heritage
Agriculture	Sustain civilization	Climate-smart agriculture	Preserve cultural landscape
Settlements	Support communities	Sustainable urban development	Maintain historic relationships
Environment	Support oasis ecosystems	Blue-green infrastructure	Protect landscape character
Tourism	Indirectly support trade	Heritage and eco-tourism	Generate conservation income
Community	Maintain canals	Local economic development	Preserve intangible heritage
Education	Transfer knowledge	Heritage interpretation	Transmit knowledge to future generations

7. Conclusions, Challenges, and Recommendation

The Dargom, Eski Angor and Eski Tuyatortar canals are exceptional examples of living irrigation heritage. Constructed more than two thousand years ago, they continue fulfilling the function for which they were originally designed, sustaining agriculture across more than 165,000 hectares while preserving an extraordinary engineering legacy. Their enduring operation demonstrates the ingenuity of ancient hydraulic engineers and highlights the resilience of traditional irrigation systems. Recognition of the Eski Tuyatortar Canal as a World Heritage Irrigation Structure reinforces the international importance of these canals and provides a foundation for broader conservation initiatives.

Beyond their historical significance, the canals possess considerable potential to become multifunctional development corridors that integrate irrigation, heritage conservation, environmental enhancement, tourism, recreation and community development. Such an approach would preserve their authenticity while generating new economic opportunities and strengthening regional resilience under changing climatic and socioeconomic conditions. The experience of Uzbekistan illustrates that ancient irrigation infrastructure need not remain solely a monument to the past. When managed through integrated planning and sustainable investment, these living hydraulic systems can continue supporting agricultural production, conserving cultural identity, enriching ecological landscapes and contributing to regional prosperity for generations to come.

Several constraints require careful management including urban encroachment, infrastructure crossings, sedimentation, declining hydraulic capacity, pollution, climate change, competing water demands, and deterioration of historic structures. Development initiatives must therefore balance modernization with conservation. Engineering interventions should preserve historical authenticity while ensuring reliable irrigation performance.

To maximize the value of these exceptional irrigation systems, the following actions are recommended:

- Prepare integrated master plans for each canal corridor.
- Establish legal protection for significant hydraulic structures.
- Develop canal heritage tourism routes linked with Silk Road destinations.
- Promote public education regarding traditional irrigation engineering.
- Introduce ecological restoration programs along canal corridors.
- Strengthen cooperation between water authorities, cultural heritage agencies and tourism organizations.
- Encourage further nominations of deserving irrigation systems for international heritage recognition.
- Develop climate-resilient operation and maintenance strategies that preserve historical characteristics while improving water management efficiency.

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