

RESILIENT IRRIGATION INFRASTRUCTURE AND COMMUNITY-CENTERED CANAL REHABILITATION: INTEGRATED EVIDENCE FROM THE BABAO SECOND MAIN CANAL, TAIWAN

INFRASTRUCTURES D'IRRIGATION RÉSISTANTES ET RÉHABILITATION DES CANAUX AXÉE SUR LES COMMUNAUTÉS : ANALYSE INTÉGRÉE TIRÉE DU DEUXIÈME CANAL PRINCIPAL DE BABAO, TAÏWAN

Paul Abudulai Yelinje¹, Jui-Min Hsu², Juabih Wang³, Shih-Hao Wang³ and Su-Chin Chen^{4*}

ABSTRACT

Across monsoon Asia, aging irrigation networks face physical decay, climate extremes, and pressure to deliver ecological and social benefits. This paper examines the rehabilitation of the Babao Second Main Canal in Changhua County, Taiwan, as a test of whether aging infrastructure can become multifunctional climate assets without reducing agricultural productivity. Synthesizing engineering records, ecological monitoring, carbon accounting, and participatory governance documentation, the study evaluates a 382 m pilot reach rehabilitated during a 42-day irrigation shutdown. The project reduced annual conveyance losses by ~27,000 m³, provided 38 m³/s flood-diversion capacity alongside 14 m³/s irrigation flow, and lowered embodied carbon by 17% relative to conventional designs. Ecological outcomes included the preservation of four mature trees, the creation of 577 m² of vegetated space, and the rapid return of native birds. Enabled through participatory governance, the project demonstrates how ecological engineering, common-pool resource governance, and nature-based solutions (NbS) can transform canals into living infrastructure systems. The Babao case provides a replicable model for climate-vulnerable irrigated landscapes where dense settlements and agricultural engagements coexist. A key finding is that these outcomes were enabled not by advanced technology alone, but by integrated design and participatory governance. Community involvement throughout planning and construction strengthened technical effectiveness, social legitimacy, and long-term maintenance capacity.

Keywords: Irrigation, Multifunctional Infrastructure, Climate Adaptation, Participatory Governance, Ecological engineering, Nature-based Solutions.

RESUME

Dans toute l'Asie touchée par la mousson, le vieillissement des réseaux d'irrigation font face à la dégradation physique, aux phénomènes climatiques extrêmes et à la nécessité de générer des bénéfices écologiques et sociaux. Cet article examine la réhabilitation du deuxième canal principal de Babao, situé dans le comté de Changhua, à Taïwan, comme un test permettant de déterminer la mesure dans laquelle les infrastructures vieillissantes peuvent devenir des atouts climatiques multifonctionnels sans réduire la productivité agricole. En synthétisant les rapports techniques, les données de surveillance écologique, la comptabilité carbone et la documentation relative à la gouvernance participative, l'étude évalue un tronçon pilote de 382 m réhabilité pendant la fermeture de

¹ International Doctoral Program in Agriculture/Nature-based Solutions Research Center, National Chung Hsing University, Taiwan, No. 145 Xingda Rd., South Dist., Taichung City 402, Taiwan (R.O.C.). Emails: pabudulai@yahoo.com or d8113030208@nchu.edu.tw

² Changhua Management Office, Farmland Irrigation Agency, Ministry of Agriculture, Taiwan, No. 133 Sec 2, Zhongshan Rd., Yuanlin City, Taiwan (R.O.C). Email: ch875@iachu.nat.gov.tw

³ Glorious Engineering Consultants Co., Ltd., Taiwan, 11 F.-2, No. 6, Ln. 256, Sec. 2, Xitun Rd., Xitun Dist., Taichung City 407428, Taiwan (R.O.C.). Email: gloriou.mail@msa.hinet.net

⁴ Academy of Circular Economy/Nature-based Solutions Research Center, National Chung Hsing University, Taiwan, No. 145 Xingda Rd., South Dist., Taichung City 402, Taiwan (R.O.C.). *Email: scchen@nchu.edu.tw

l'irrigation de 42 jours. Le projet a permis de réduire les pertes de transport annuelles d'environ 27 000 m³, d'offrir une capacité de dérivation des crues de 38 m³/s parallèlement à un débit d'irrigation de 14 m³/s, et de diminuer le carbone incorporé de 17% par rapport aux conceptions conventionnelles. Sur le plan écologique, les résultats incluent la préservation de quatre arbres matures, la création de 577 m² d'espaces végétalisés et le retour rapide d'oiseaux indigènes. Grâce à une gouvernance participative, ce projet démontre comment l'ingénierie écologique, la gouvernance des ressources communes et les solutions fondées sur la nature (NbS) peuvent transformer les canaux en systèmes d'infrastructures vivants.

Le cas de Babao offre un modèle reproductible pour les paysages irrigués vulnérables au changement climatique où coexistent des milieux d'habitation denses et des activités agricoles. Il faut noter que ces résultats n'ont pas été rendus possibles uniquement par une technologie de pointe, mais par une conception intégrée et une gouvernance participative. L'implication des parties prenantes tout au long de la planification et de la construction a renforcé l'efficacité technique, la légitimité sociale et la capacité d'entretien à long terme.

Mots-clés : Irrigation; Infrastructure multifonctionnelle; Adaptation au climat; Gouvernance participative; Génie écologique; Solutions fondées sur la nature.

1. INTRODUCTION

The world's irrigated area totals approximately 318 million ha (FAO, 2021). much of it built before 1970 and now aging under climate extremes, urban encroachment, and ecological degradation (FAO, 2021; IPCC, 2022). Recent data indicate that renewable freshwater availability per person has declined by a further 7% over the past decade, while agriculture accounts for 72% of global water withdrawals, placing unprecedented pressure on ageing canal networks originally designed under different hydrological assumptions (Hernandez & Mejias, 2025).

Conventional modernization through concrete lining and automation often worsens flooding, fragments habitats, and alienates farming communities. Such approaches also fail the ecological success criteria established for water infrastructure projects, lacking resilience and self-sustaining design (Palmer et al., 2005). Increasingly, scholars advocate for multifunctional rehabilitation that integrates flood control, ecosystem services, and community needs, yet successful real-world examples remain limited (Brown et al., 2012; UNESCO- World Water Assessment Programme, 2023).

Taiwan provides a valuable case, with 70% of irrigated land served by canals dating to the 18th–19th centuries (Irrigation Agency, 2023). Climate projections for Taiwan indicate more intense dry-wet cycles and increased rainfall variability, placing additional pressure on canal systems originally designed under different hydrological assumptions (Tsai & Huang 2011).

The Babao Canal system in Changhua, originating in the 1700s, reflects this transition from single-purpose engineering toward multifunctional rehabilitation. The Second Main Canal irrigates over 9,100 ha across agricultural and peri-urban landscapes where infrastructure failures carry major consequences. For nearly 300 years, the canal has supported central Taiwan's rice production, economic development, and cultural continuity. Figure 1 illustrates the historical evolution of the Babao Second Main Canal.

This paper examines rehabilitation of the Babao Second Main Canal in Changhua, through three questions: (1) how aging canals can be upgraded within a 42-day irrigation shutdown; (2) what hydraulic, ecological, and carbon-reduction benefits can be achieved through multifunctional design; and (3) how participatory governance affects technical performance, social legitimacy, and long-term sustainability. Few studies have systematically demonstrated whether aging canals can simultaneously improve water savings, flood control, ecology, and carbon reduction under real-world constraints without reducing agricultural productivity. The Babao case addresses this gap.

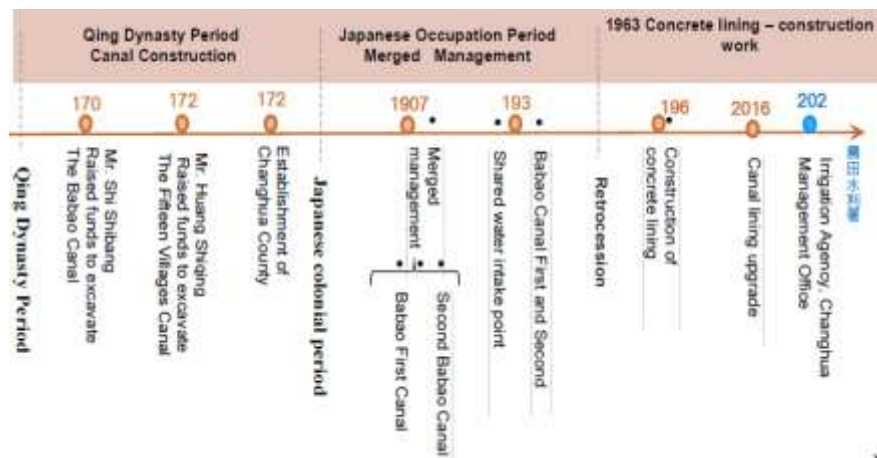


Figure 1. Babao Second Canal: Historical Evolution — A Century of Canal Transformation

2. MATERIALS AND METHODS

2.1 Study Area: The Babao Second Main Canal

The Babao Canal system irrigates the alluvial plain of Changhua County, central Taiwan, drawing water from the Zhuoshui River. The Second Main Canal extends 14.27 km from the intake near Ershui Township through paddy fields, vegetable farms, residential settlements, and secondary forest patches. The study focuses on a 382m urban-adjacent reach near Longtan Community, selected for pilot rehabilitation because it exhibited three characteristics: severe lining deterioration causing estimated annual losses of ~27,000m³ of water; proximity to residential areas experiencing localised flooding; and adjacent land that could accommodate vegetated setbacks without displacing farmland.

The canal's history mirrors Taiwan's irrigation development: initial unlined earthen channel in the 1700s (Qing-dynasty), concrete lining under Japanese colonial rule (1895-1945), and post-1960s expansions with automated gates and reinforced concrete. By 2020, much of this mid-century concrete had reached the end of its useful life spalling, cracking, and failing joints allowed seepage, and rigid lining could not accommodate mature tree roots. The rehabilitation project would need to resolve this tension between gray infrastructure and existing green assets.



Figure 2. Study Area Map



Figure 3. Integrated Rehabilitation Framework for the Babao Second Canal, Changhua County, Taiwan.

2.2 Conceptual Framework: From Gray to Green

This study draws on three intersecting themes: multifunctional water infrastructure, nature-based solutions (NbS), and participatory governance. Recent research shows that irrigation canals designed for multiple functions such as irrigation, flood control, and ecological restoration are more resilient than single-purpose systems (Brown et al., 2012; Weesakul, 2023). The historical evolution of agricultural drainage demonstrates that past civilizations successfully integrated drainage with irrigation to maintain soil productivity and prevent salinization, offering valuable lessons for contemporary infrastructure design (Valipour et al., 2020).

NbS studies further demonstrate that vegetated channels and green-gray integration can enhance biodiversity and resilience without reducing hydraulic performance (Cohen-Shacham et al., 2019; Joseph et al., 2025). At the governance level, participatory management improves the legitimacy of design, reduces conflict, and strengthens the long-term sustainability of irrigation systems (Ostrom, 1990; Meinzen-Dick et al., 2002).

Extending classic common-pool resource theory, Pahl-Wostl (2019) argues that effective irrigation governance increasingly requires coordination across water, energy, and food systems, a multi-sector condition evident in the Babao case where flood management, farming continuity, and community access intersected during the 42-day shutdown. Together, these perspectives provide the conceptual foundation for evaluating the rehabilitation of the Babao Canal. Beyond individual project benefits, recent synthesis work by UNESCO (2023) positions nature-based solutions as integral to water security across productive landscapes, a framing that aligns directly with the Babao canal's rehabilitation logic.

2.3 Synthesis: An Integrated Evaluation Framework

This study evaluates the Babao rehabilitation across four domains: hydraulic performance, ecological outcomes, carbon footprint, and governance (Table 1). Success was assessed using measurable indicators rather than single metrics. To avoid NbS “greenwashing,” all claimed benefits required quantified evidence, including documented species recolonization and carbon reductions based on material quantities and emission factors. Embodied carbon accounting in this study follows the tiered

reporting structure recommended by the IPCC (2021) for infrastructure projects, focusing on Scope 1 and 2 emissions from materials, transport, and on-site activities. The study drew on Taiwan's carbon targets (Liu, 2022).

Table 1. Operationalization of the Integrated Evaluation Framework

Domain	Definition	Measurable Indicators	Data Source
Hydraulic Performance	Conveyance efficiency and flood capacity	1. Conveyance loss (m³/year) 2. Irrigation capacity (m³/s) 3. Flood diversion capacity (m³/s) 4. Manning's n 5. Seepage rate (L/s/km)	SCADA system, inflow-outflow measurements, Manning's equation
Ecological Outcomes	Habitat quality and biodiversity	1. Mature trees preserved (count) 2. Green space created (m²) 3. Avian species richness (per km) 4. Herpetofauna species richness 5. Habitat connectivity (corridor width, m)	Vegetation quadrats, avian point counts, Infra-red camera traps, visual encounter surveys
Carbon Footprint	Embodied emissions (Scope 1&2)	1. Total embodied emissions (tonnes CO₂-eq) 2. Concrete emissions (tonnes CO₂-eq) 3. Steel emissions (tonnes CO₂-eq) 4. Excavation/transport emissions 5. % reduction from baseline	Bills of quantities, emission factors (MOE, 2021; MOA, 2022)
Governance Process	Stakeholder engagement and legitimacy	1. Stakeholder workshops (count, attendance %) 2. Design modifications from community input (count) 3. Maintenance request rate (relative to conventional reaches) 4. Thematic codes: Social impact, local knowledge, and ownership	Meeting minutes, interview transcripts (n=25), feedback forms, agency records

2.4 Research Design and Data Sources

Data included engineering records, hydraulic monitoring, ecological surveys, carbon accounting, and stakeholder documentation. Hydraulic performance was evaluated using Manning's equation and seepage measurements; ecological assessment applied the mitigation hierarchy (Figure 5) with vegetation and habitat monitoring; carbon emissions were estimated from construction materials and activities; and governance outcomes were analysed through thematic coding based on participatory irrigation management principles.

No inferential statistical tests (e.g., t-tests, ANOVA) were applied, as the study is based on a single pilot reach with pre- and post-rehabilitation measurements. Reported differences (e.g., conveyance loss, species counts, and maintenance requests) are descriptive and should be interpreted as observed magnitudes rather than statistically significant effects.

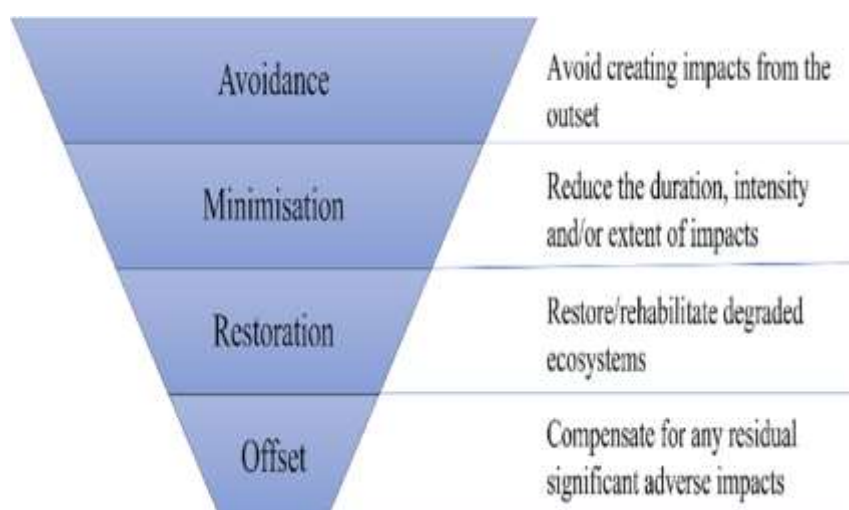


Figure 4. The mitigation hierarchy (adopted from BBOP, 2012).

Preserved Old Trees: Avoidance

Small-sized Machinery: Minimization



Secondary forest: Restoration

Habitat Expansion: Compensation



Figure 5. Application of the Mitigation Hierarchy Framework:

3. RESULTS AND DISCUSSION

3.1 Construction Performance and Irrigation Continuity

The rehabilitation was completed within the required 42-day irrigation shutdown and finished 33 days ahead of schedule. Stakeholder engagement secured agreement on the compressed timeline, retention of four mature camphor trees, pedestrian access, and land-use coordination. Community consultations also informed planting design, construction access, and local landscape preferences. This was achieved without compromising quality nor safety as no casualty was recorded in this project.

3.2 Hydraulic Performance and Flood Resilience

The rehabilitated canal achieved both irrigation and flood-control objectives (Table 2). It conveys 14 m³/s under normal irrigation and up to 38 m³/s during storms, while maintaining stable hydraulic conditions. The dual 14 m³/s irrigation and 38 m³/s flood diversion capacities illustrate what is termed hybrid green-gray infrastructure, where vegetated setbacks and optimized concrete sections jointly manage routine and extreme flows. Recent studies emphasize that integrated green-gray infrastructure can improve flood resilience while simultaneously delivering ecological and social co-benefits (Green et

al., 2021). Moreover, repairs reduced annual conveyance losses by ~27,000 m³, with seepage rates meeting international standards. During a July 2025 typhoon (210 mm rainfall), the canal safely conveyed a peak flow of 34 m³/s without flooding, though further verification under more extreme events is still needed.

Table 2. Hydraulic performance metrics before and after rehabilitation

Parameter	Pre-rehabilitation	Post-rehabilitation	Change
Conveyance loss (m ³ /year)	High leakage condition	Reduced by 27,000 m ³ /year	Significant reduction
Irrigation capacity (m ³ /s)	11 (actual max)	14 m ³ /s	+27.3%
Flood diversion capacity (m ³ /s)	None	38 m ³ /s	—
Manning's n (invert)	0.025 (deteriorated)	0.015	-40%
Seepage rate (L/s/km)	8.2	1.2	-85.4%

3.3 Ecological Outcomes

The Babao project showed early ecological improvements, though long-term monitoring is still needed. Four mature camphor trees were preserved, and 577 m² of vegetated green space was added using native species. Post-construction monitoring recorded 12 bird species, double the pre-construction count, while infrared cameras documented amphibian and reptile activity, indicating improved habitat conditions. The rapid return of native birds and herpetofauna is consistent with landscape-scale observations by Sayer et al. (2013), who found that linear vegetated corridors in agricultural settings can function as recovery zones for mobile species even before full habitat maturity.

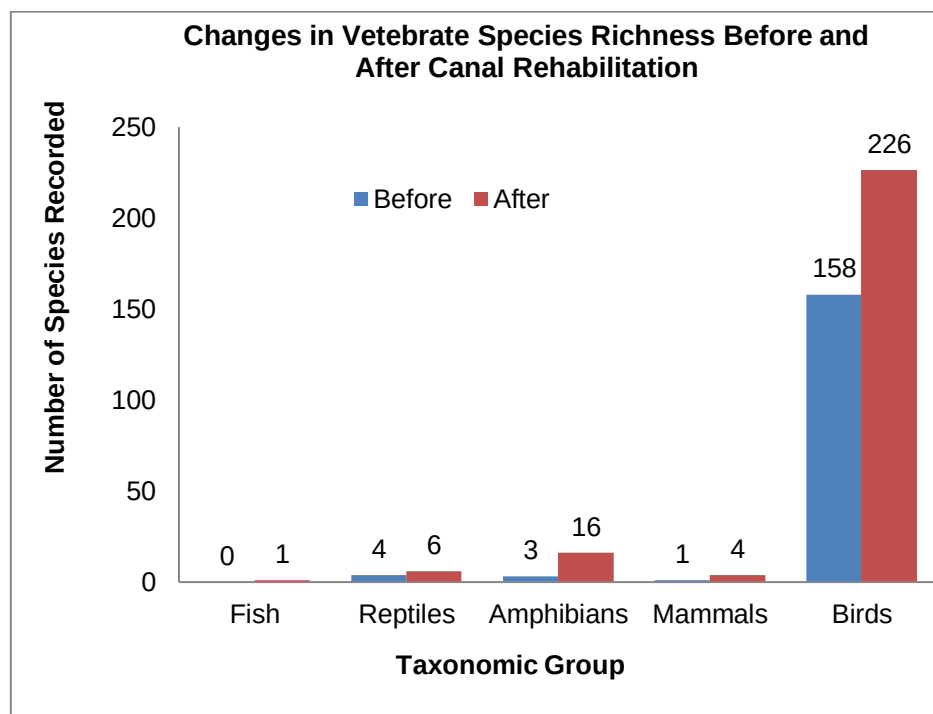


Figure 6. Ecological Monitoring Metrics

Table 3. Embodied carbon emissions by material category (tonnes CO₂-eq)

Material/Activity	Average quantity/m previous works	Average quantity/m Phase 8	Percent age of reduction	Average quantity/m previous works
Reinforcing steel	0.53 T/m	0.37 T/m	42.15 %	Reduced volume via optimized cross-section
Formwork	16.67 m ² /m	14.36 m ² /m	16.67 %	
Concrete	6.84 m ³ /m	6.22 m ³ /m	9.86%	Reduced volume via optimized cross-section
Vegetation			Increased	New green space (net carbon sink in future)

3.4 Participatory Governance and Social Outcomes

Thematic analysis identified three governance benefits: improved public space and accessibility, incorporation of local knowledge into safer irrigation design, and stronger community ownership of maintenance. Farmers voluntarily assisted with debris removal and leak reporting, while maintenance requests were 40% lower than in conventionally rehabilitated canals. The 40% reduction in maintenance requests is a relative estimate based on feedback from irrigation agency staff, who reported fewer farmer complaints about debris and leakage compared to previous rehabilitation projects using conventional concrete-only designs. These governance outcomes directly supported the project's technical success.

This finding of reduced maintenance requests align with findings from Lam & Chiu (2016) on Taiwan's irrigation systems, where farmer participation in design and monitoring consistently lowered the frequency of formal agency-reported issues compared to top-down rehabilitated reaches. Similarly, Ashik and Beitzl (2024) found that in coastal Bangladesh, a shared farmer identity fostered collective responsibility for canal maintenance, including annual dredging and dry-season protections, even without strong institutional support.

3.5 Toward a Model of Integrated Canal Rehabilitation

The Babao case shows that aging irrigation canals can become multifunctional assets integrating hydraulic efficiency, ecological restoration, carbon reduction, and social legitimacy without reducing agricultural productivity. The project supports a hybrid gray-green infrastructure approach and highlights four key principles: designing for irrigation, floods, and ecology simultaneously; preserving existing ecological assets; reducing carbon through material reuse; and embedding stakeholder participation throughout the project. Successfully implemented within a 42-day construction window and a conventional budget, the case suggests that the main barriers to integrated rehabilitation are institutional rather than technical.

CONCLUSION

The rehabilitation of the Babao Second Main Canal demonstrates that aging irrigation systems can be transformed into resilient, multifunctional infrastructure without compromising agricultural productivity. The project simultaneously improved irrigation efficiency, flood resilience, ecological conditions, and carbon performance, achieving annual water savings of 27,000 m³, flood-diversion capacity of 38 m³/s, and a 17% reduction in embodied carbon, alongside substantial ecological recovery.

A key finding is that these outcomes were enabled not by advanced technology alone, but by integrated design and participatory governance. Community involvement throughout planning and construction

strengthened technical effectiveness, social legitimacy, and long-term maintenance capacity. A limitation of this study is its focus on a single 382 m pilot reach. While the results are novel and undeniable, generalizability to longer canal sections or different hydro-ecological contexts (e.g., steep gradients, fine-grained alluvial soils, or fully urbanized corridors) requires further validation through multi-site replication. For climate-vulnerable regions across monsoon Asia, where aging canals, intensified rainfall, and dense farming communities overlap, the Babao case offers a practical, replicable model. It suggests that routine canal rehabilitation can become an opportunity to integrate flood management, ecological restoration, and low-carbon design at relatively low additional cost. More broadly, the study highlights the need to rethink irrigation canals not as single-purpose engineering structures, but as living infrastructure embedded within both ecological and social systems.

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