Proceedings of CONF-MCEE 2026 Symposium: Geomaterials and Environmental Engineering
DOI: 10.54254/2755-2721/2026.MH31749

A Comparative Case Study of Ecological Restoration Models and Collaborative Governance in Typical Fluctuation Zones of the Three Gorges Reservoir Area

Shijing Tang

Institute of Environment and Energy, City University of Hong Kong, Hong Kong, China
shijitang8-c@my.cityu.edu.hk

Abstract. The inundation zone within the Three Gorges Reservoir area, formed by the reservoir's 'clear water storage and turbid water discharge' operation, serves as a crucial aquatic-terrestrial buffer zone maintaining ecological equilibrium. However, in recent years, multiple degradation risks have emerged, including micro-topographical fragmentation and homogenisation, vegetation decline, and a sharp reduction in biodiversity, directly threatening the reservoir's ecological security. This study, therefore, examines three representative inundation zones within the reservoir area: Wuyangba, Zhongxian-Shizhu, and Xiangxi River. By comparing the differences in their degradation characteristics, the study identifies the manifestations and driving mechanisms of ecological degradation in each area. Building on this, the research further integrates and evaluates ecological restoration technology systems tailored to different types of degradation, proposing new developmental directions for addressing the complex degradation issues in reservoir fluctuation zones. This study aims to provide systematic scientific evidence for the systematic restoration of the Three Gorges Reservoir area, as well as theoretical references and practical templates for the ecological governance of similar reservoirs.

Keywords: Three Gorges Reservoir area, Inundation Zone, Ecological Restoration, Microtopography, Plant Community, Heavy Metal Remediation

1. Introduction

The Three Gorges Reservoir constitutes China's largest water control project. It employs the strategy of "storing clear water and discharging turbid water". Consequently, extensive inundation zones have formed in the reservoir area. These zones have dual aquatic and terrestrial ecological attributes, serving as core regions for maintaining ecological stability. However, periodic water-level fluctuations, compounded by human disturbance and disorderly development, have led to significant ecological degradation in these inundation zones. Moreover, microtopography has become increasingly homogenised and fragmented, leading to a sharp decline in biodiversity and soil heavy metal accumulation. Consequently, the reservoir's soil conservation and pollutant purification functions have been compromised, posing threats to water resource security and biodiversity within the reservoir area.

To address habitat homogenisation and vegetation degradation in the water-level fluctuation zone, researchers have pursued technical solutions through multiple pathways. Some scholars have sought methods to enhance habitat heterogeneity, combining microtopography modification with improved plant combinations [1,2]. Additionally, Zou et al. developed elevation-gradient vegetation configuration patterns based on flood tolerance [3,4]. Li Wenqiao et al. employed native plants selected for specific remediation of heavy metal contamination [5].

However, existing research mainly focuses on single-dimensional issues and lacks a systematic analysis of framework. This paper reviews relevant literature to select three representative remediation sections, clarifying degradation characteristics and causes while comparing remediation techniques and outcomes. It aims to synthesise applicable technical pathways for reservoir ecological security and similar drawdown zone management.

2. Overview of study areas

The Three Gorges reservoir drawdown zone extends along the main Yangtze River and its major tributaries. This area is situated within a subtropical monsoon climate. The annual average temperatures range from 18 to 19°C, with annual precipitation of 1000–1200 mm concentrated during the April–September rainy season. The core reservoir area maintains moderate humidity conducive to vegetation development. The water regulation strategy of “clear water storage and turbid water discharge” drives an inverse seasonal rhythm. Water levels rise in winter and fall in summer, with low levels in summer and high levels in winter. Annual fluctuations can reach up to 30 metres. Flood duration decreases with increasing elevation. Regional topography is highly undulating, with interlocking mountains and hills. The Wuyangba section shows transitions between hard-lined revetments and natural earthen banks. Sediment deposition and human disturbance have concurrently homogenised and fragmented local landforms. Consequently, three representative areas were selected for study: the Wu Yangba inundation zone in Kaizhou District, Chongqing; the Zhongxian-Shizhu inundation zone; and the Zigui section of the Xiangxi River. These sites exhibit distinct differences in topography, vegetation, and ecological issues, providing representative locations for the development and demonstration of categorised restoration techniques.

3. Comparative analysis of ecological degradation characteristics in typical areas

To systematically analyse the spatial differentiation of degradation in the Three Gorges reservoir zone's inundation zones, this chapter compares the dominant degradation characteristics across three representative areas.

3.1. Degradation characteristics of the floodplain zone in the Zhongxian–Shizhu section

Situated in the heart of the Three Gorges reservoir area, this region serves as a crucial ecological transition zone. The main challenges stem from periodic inundation, sediment accumulation, and human disturbance, specifically cultivation and sand extraction. Floodplain water levels between Zhongxian and Shizhu fluctuater rhythmically. With each cycle, persistent sediment is deposited, steadily smoothing the original contours of the slopes. Meanwhile, sand extraction and slope reclamation dissect the slope mass, producing a landscape now characterised by “homogeneous slopes and fragmented plots” [1]. Microhabitats conducive to species coexistence, such as rock crevices and low-lying waterlogged areas, have been nearly eradicated. Compounded by soil heavy metal accumulation, the migration of these metals via water and sediment further undermines slope

DOI: 10.54254/2755-2721/2026.MH31749

stability, triggering a degradation cascade characterized by sharp species decline and ecological dysfunction. Repeated agricultural and other human activities accelerate the build-up and movement of heavy metal accumulation, further polluting the soil. Consequently, microhabitats have nearly vanished, slope stability has weakened, and both species diversity and ecological functions have markedly declined [5].

3.2. Degradation characteristics of the receding water zone in the Xiangxi River section

The Xiangxi River's inundation zone, as a tributary flowing into the reservoir, exhibits structural degradation in its vegetation communities. This degradation results from the interaction of periodic waterlogging stress and specific site conditions. The primary manifestations are a trend towards species composition becoming increasingly monotonous and the succession of dominant species. Following reservoir impoundment, the original tree-shrub-grass composite system disintegrated. Annual herbaceous plants now constitute over half the vegetation, with Asteraceae and Poaceae dominating. This shift has left only six tree species, representing a significant decline in species richness compared to pre-impoundment conditions. The decline in tree and shrub species has directly reduced ecological functions such as soil retention and water conservation. Moreover, species distribution has become more pronounced along the elevation gradient, producing a V-shaped diversity pattern: lower elevations are dominated by Bermuda grass and Cyperus rotundus, mid-elevations feature species like Echinochloa crus-galli, while higher elevations comprise relatively diverse communities of Setaria viridis and Xanthium strumarium [6]. Importantly, site factors such as elevation, duration of flooding, soil moisture, and slope gradient interact to drive these changes. Mid-to-high elevation zones, though experiencing moderate flood duration, exhibit fragmented topography and severe soil erosion, making them the most intensely degraded areas [6].

3.3. Degradation characteristics of the Wuyangba water-level fluctuation zone

Regional degradation in the Wuyangba inundation zone manifests as concurrent terrain fragmentation and homogenisation. Its core predicament lies in the synchronous degradation of topography and vegetation, ultimately undermining habitat functionality for fauna. Sediment deposition, cultivation, quarrying, sand extraction, and hard revetment construction have repeatedly levelled the terrain, fragmenting it locally and erasing micro-topographic variations. This disrupts habitat continuity and nearly eliminates the spatial differentiation of ecological niches—a feature essential for species coexistence. Prolonged waterlogging further suppresses native vegetation, resulting in a dominant monoculture of weeds with extremely low species richness [1]. This dual destruction has compressed animal habitats: winter inundation permits only brief stopovers for a few waterfowl, while the thin secondary herbaceous layer exposed in summer fails to provide the multi-layered structure needed for shelter, foraging, and reproduction. Consequently, local both the diversity and abundance of local animal species have plummeted, leading to the collapse of food chains. This fundamentally represents irreversible loss of habitat heterogeneity, triggering simplification of system structure and functional decline, ultimately manifesting as synchronous reduction in both plant and animal diversity.

DOI: 10.54254/2755-2721/2026.MH31749

4. Ecological restoration techniques for typical regions of the Three Gorges reservoir zone

4.1. Micro-topography–plant synergistic restoration in the Zhongxian–Shizhu fluctuation zone

To address the compound challenges of fragmented topography, soil heavy metal contamination, and ecological decline in the Zhongxian-Shizhu floodplain zone, existing research and practice have integrated a three-pronged remediation approach: micro-topography modification, biotechnical stabilization, and synergistic remediation of heavy metals. This framework requires breaking the cycle of habitat homogenisation and stabilising substrates. For instance, terraced platforms are deployed at lower elevations, with concave channels between terraces to trap sediment and rainwater. In sand-dredged disturbance zones, ecological bags filled with gravel form porous revetments, complemented by ecological ditches to enhance erosion control and pollution reduction. Topographical modification creates heterogeneous habitat substrates for ecological recovery. The integration of vegetation with modified micro-topography and pollution gradients facilitates slope stabilization, concurrently promoting plant establishment and the extraction of heavy metals. Existing research typically plants flood-tolerant, soil-stabilising species such as Rumex acetosa and Cd-accumulating Cyperus rotundus in low-flood zones, while selecting composite pollution remediation species such as Bermuda grass and shrubby willow for slope stabilisation at medium-high elevations.

Additionally, some scholars propose planting deep-rooted bald cypress trees at higher elevations, intercropped with Cd-stable bitter vetch. Promoting vegetative-grass cover and integrated water-fertiliser management enhances soil fertility and plant survival rates. Research confirms this system markedly enhances slope erosion resistance, restores habitat heterogeneity, and reduces soil Cd levels by 30–40%. This has led to substantial mitigation of terrain degradation, soil erosion, and heavy metal contamination [5,7].

4.2. Xiangxi River floodplain zone: elevation-gradient-based native vegetation configuration technique

The primary challenge facing the Xiangxi River's inundation zone is ecological decline and simplified vegetation structure due to periodic flooding. Current restoration approaches primarily employ integrated management systems based on elevation gradients to encourage near-natural vegetation recovery. This approach requires in-depth study of vertical habitat differentiation within the inundation zone to inform appropriate models. Extensive research highlights the importance of identifying critical limiting factors(e.g., flood duration and soil conditions), and then selecting native species that are well-adapted to these conditions, and then establishing a three-tiered community structure based on flood duration. At low elevations, rapid revegetation is achieved using species such as Bermuda grass and saltbush. At medium-high elevations, stability is ensured by establishing composite perennial herbaceous communities through judicious combinations of native dominant species. High-elevation zones prioritise long-term objectives of restoring the tree layer and complex structural integrity.

Consequently, the study endeavours to compare multiple targeted planting techniques. For instance, seed spraying is employed on gentle terrain, while on steep slopes, auxiliary methods such as three-dimensional mesh spraying are utilized [6]. In ecologically sensitive zones, pilot applications of ecological concrete and soil bioengineering have been employed. Post-restoration, regular pruning and reseeding maintained high vegetation coverage, ultimately effectively managing

DOI: 10.54254/2755-2721/2026.MH31749

1.94 km² of eroded land. As a result, the restored areas exhibited significantly reduced soil erosion rates and a marked recovery in local species richness [8].

4.3. Wuyangba floodplain: near-natural habitat restoration and species diversity enhancement

The Wuyangba drawdown zone faces challenges including habitat heterogeneity loss, biodiversity decline, and increased pressure on ecological services. In response to these issues, current restoration practices increasingly adopt a comprehensive technical approach centred on near-natural habitat restoration and targeted enhancement of species diversity. The specific implementation pathway involves: The first step involves systematically constructing composite micro-topographic units, such as linear concave channels, terraced wooded marsh belts, and multi-void revetment zones, alongside depressions, ponds, and earthen mounds, to form a wooded marsh composite system. Simultaneously, gabion embedding and soil matrix improvement are undertaken to correct topographical deficiencies while reinforcing slopes. Building upon this foundation, vegetation selection follows zonal characteristics, employing flood-tolerant trees, shrubs, and native herbaceous species to establish multi-layered, near-natural communities. This approach aims to activate the soil seed bank, facilitating natural species regeneration [1].

The advantage of this approach lies in its ability to guide ecosystem restoration towards re-establishing food web integrity while optimizing species composition and spatial distribution. Practice demonstrates that this system significantly increases plant species diversity, concurrently enhancing the structural stability and ecological service functions of the inundation zone. It provides a replicable model for biodiversity conservation in urban inundation zones [7].

5. Assessment and limitations of ecological restoration techniques in Three Gorges reservoir zone floodplains

5.1. Multidimensional comprehensive outcomes of floodplain restoration

Table 1. Comparison of restoration effects across three typical floodplain zones [9]

Evaluation Dimensions	Wuyangba	Zhong - Stone Steps	Xiangxi River
Structural Stability	The interlocking arrangement of concave channels, terraces and porous revetments significantly enhances bank heterogeneity, leading to a sharp reduction in surface soil erosion and stabilising the river section.	The shoreline has stabilised, with reduced erosion	Continuous slope vegetation cover significantly increases the area protected from soil erosion, substantially reducing rainfall erosion intensity
Species Diversity	Formation of tree-shrub-grass composite communities	Optimised vegetation community structure with enhanced species richness	Vegetation coverage approaches full coverage, forming mixed composite plant communities
Biodiversity	Significant increase in recorded bird species, establishing a vital wintering ground for waterfowl	Habitat improvement, optimised animal habitats, and gradual restoration of species diversity	Native fauna returning, rare waterfowl populations increasing, and food chain integrity enhanced
Heavy Metal Remediation	Targeted plant combinations achieve significant removal rates for heavy metals such as cadmium, mitigating potential ecological risks	Soil heavy metal concentrations reduced through phytoremediation, controlling pollution risks	Synergistic effects of plant combinations and electro-remediation technologies enhance heavy metal purification efficiency
Landscape quality	Creates a richly varied composite landscape with alternating elevations and seasonal phases	Enhanced harmony between shoreline ecological landscapes and surrounding environments	Achieving the transformation objectives of "clear waters, green banks, and beautiful scenery"

DOI: 10.54254/2755-2721/2026.MH31749

As shown in Table 1, all three ecological restoration techniques produced multidimensional integrated effects. Integrating vegetation with engineering measures enhanced structural stability and disturbance resistance while reducing soil erosion, thereby maintaining river section stability. Concurrently, long-term systematic restoration progressively enhanced plant species richness and improved community structure, thereby increasing overall biodiversity. oth ecological and social benefits were realized. Electro-assisted phytoremediation further enhanced purification efficiency, mitigating potential environmental and health risks [9].

The three restoration approaches examined herein all prioritise “near-natural restoration” as their guiding principle. Tailored technical combinations address regionally dominant issues, driving holistic ecosystem improvement and forming a categorically precise technical framework. The Zhongxian-Shizhu section emphasises micro-topography modification, biotechnical stabilization, and synergistic heavy metal remediation, concurrently achieving structural stability and pollution control. The Xiangxi River section concentrates on gradient configuration and functional restoration. The Wuyangba section focuses on habitat reconstruction and the enhancement of diversity. All three approaches utilise native species as a foundation and hydrological rhythms as a cadence, balancing structural stability, biodiversity, and landscape optimisation. They provide directly replicable technical templates for similar floodplain sections.

Therefore existing research indicates that these remediation approaches are not mutually exclusive but should be integrated into a unified management strategy. Through three-tiered coordination at slope, micro-basin, and regional levels, terrain stabilisation, vegetation matching, pollution control, and habitat optimisation are progressively implemented, forming a synergistic response. This significantly enhances the structural integrity and functional sustainability of the drawdown zone ecosystem, yielding overall benefits far exceeding the simple sum of individual techniques.

5.2. Limitations

The variability in ecosystem restoration outcomes is constrained by both human interventions and environmental factors. Flood duration directly influences plant selection and community assembly. Factors such as soil moisture content, nitrogen and phosphorus concentrations, and air temperature affect community patterns. Persistent disturbances from human activities—including cultivation, quarrying, and tourism—constitute the primary causes of restoration failure.

Furthermore, the current reservoir ecological restoration technology system faces multiple bottlenecks. The mechanisms underpinning microtopography-plant interactions remain unclear, hindering precise technical design. Heavy metal phytoremediation is time-consuming and technically demanding, and current plant-electric coupling remediation lacks optimisation of engineering parameters (e.g., electrode placement, voltage gradients) and suffers from insufficient mechanistic research. Due to the scarcity of long-term monitoring data in reservoir areas, assessment of remediation effectiveness currently lacks sustained evidence.

5.3. Future directions

Ecological restoration of the Three Gorges reservoir's inundation zone necessitates long-term, systematic management that address technical bottlenecks and practical requirements. Clarifying multi-scale coupling mechanisms and suitability for unique sites forms the foundation, requiring quantification of microtopography-plant interactions, identification of optimal remediation parameters for extreme habitats, and addressing technical shortcomings. Further development of synergistic remediation technologies involving plants and microorganisms is essential to tackle complex pollution [10]. Establishing a digital twin-driven dynamic regulation platform constitutes another critical measure. Integrating integrated airborne, terrestrial, and space-based monitoring with ecological simulation will form a closed-loop information system of “monitoring-simulation-regulation-feedback,” enabling real-time control of restoration outcomes [11]. Ultimately, this will propel the fluctuation zone toward precision-driven, systematic development and synergistic optimisation across ecological, economic, and social dimensions [12].

6. Conclusion

This study selected three representative drawdown zones—Zhongxian-Shizhu, Xiangxi River, and Wuyangba—to investigate their primary degradation factors. Findings reveal Zhongxian-Shizhu faces dual pressures from terrain degradation and heavy metal pollution, that the Xiangxi River exhibits declining vegetation community structure, and that Wuyangba demonstrates systematic biodiversity decline. This paper further proposes tailored research approaches for each site, all emphasising the coupling of terrain and vegetation, prioritising native species, and implementing measures aligned with hydrological rhythms. These technical solutions have achieved varing degrees of slope stabilisation, enhanced biodiversity, reduced pollution, and optimised landscapes to varying degrees.

Nevertheless, this study has certain limitations. Quantitative insights into the specific coupling of multiple processes remain insufficient, primarily relying on existing literature and data. An In-depth exploration of addressing composite pollution, extreme site conditions, and long-term adaptive management has yet to be undertaken. Future research should incorporate additional variables, conduct long-term monitoring of reservoir restoration outcomes, and advance restoration practices towards a new paradigm characterised by precision, systematisation, and intelligence.

References

[1] Yang, L. Q., Chen, H. F., You, F. Y., et al. Design and evaluation of synergistic micro-topography-plant restoration in urban inundation zones of the Three Gorges Reservoir area [J]. Chinese Urban Forestry, 2024, 22(4): 1-9.
[2] Zhu, Z. W., Zhong, W. J., Liao, W., et al. (2025). Ecological integrated restoration technologies and applications for reservoir tailwater zone fluctuation zones. Bulletin of the Yangtze River Scientific Research Institute, 42(2), 69–75.
[3] Zou, X. C., Wei, Z. K., Wang, T. W., et al. (2026). Plant community composition and distribution characteristics of bank slopes and fluctuation zones in the Three Gorges Reservoir area. Acta Ecologica Sinica, 46(1), 1–14.
[4] Tian, R. J., Yang, Y. C., & Li, H. (2025). Study on vegetation characteristics in the fluctuation zone of the Three Gorges Reservoir area. Acta Ecologica Sinica, 45(16), 8178–8188.
[5] Li, W. Q. (2021). Research on the remediation potential of dominant species in the fluctuation zone of the Three Gorges Reservoir area for heavy metal-contaminated soil [Master’s thesis]. Southwest University.
[6] Hu, M. X., Zhu, H. F., Wang, X. Y., Hu, D. L., Chen, H. Y., Li, P. P., Li, X. L., & Huang, G. Y. (2025). Plant community structure and characteristics in the inundation zone of Xiangxi River, Three Gorges Reservoir. Acta Botanica Sinica 43(5): 583-593. DOI: 10.11913/PSJ.2095-0837.24277.
[7] Gou, M. M., Liu, C. F., Wang, Y. Q., et al. (2025). Near-natural ecological restoration and ecological security assurance in the ecological barrier zone of the Three Gorges Reservoir area. Chinese Journal of Soil and Water Conservation (Chinese and English). Advance online publication.
[8] Ye Jing, Wan Bin, Shen Gang, et al. Ecological Restoration Engineering Practices in Reservoir Fluctuation Zones: A Case Study of the Xiangxi River Basin Comprehensive Management and Restoration Project (Zigui Section) in the Three Gorges Reservoir Area. China Environmental Protection Industry, (11): 30-33.
[9] Nie, H. Y. (2025). Heavy metal pollution characteristics and phytoremediation technology in the fluctuation zone of the Three Gorges Reservoir area [Master’s thesis]. Three Gorges University. https: //doi.org/10.27270/d.cnki.gsxau.2025.000175

DOI: 10.54254/2755-2721/2026.MH31749

[10] Cui, J., Peng, Y., Zhou, Y., et al. (2024). Progress in the application of invasive aquatic plants in ecological remediation of polluted water bodies in China. Journal of Plant Resources and Environment, 33(1), 1–13.
[11] Jiao, H., He, Z., Guo, Q., et al. (2025). Spatiotemporal evolution and driving mechanisms of ecological environment quality in the Three Gorges Reservoir area (Chongqing Section) based on remote sensing ecological indices. Three Gorges Ecological Environment Monitoring, 10(3), 55–66. https: //doi.org/10.19478/j.cnki.2096-2347.2025.03.06
[12] Ma, L. (2022). Assessment and optimisation of publicness in urban recreational spaces within the Three Gorges Reservoir area [Doctoral dissertation]. Chongqing University. https: //doi.org/10.27670/d.cnki.gcqdu.2022.003837