

Toward Resilient Hydro-Ecological Infrastructure: A “Four Capacities” Framework for Sustainable Development

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1 Introduction

Water is the source of life, the lifeblood of ecosystems, and a critical pillar in China’s vision for ecological civilization. Against the backdrop of intensifying climate change, increasing water-related disasters, and mounting pressure on the ecological carrying capacity, we must reexamine the regulatory and supporting functions of water ecosystems. The time has come to move beyond rigid, single-purpose water management models and return to nature-based, ecologically adaptive approaches to building resilient hydro-ecological infrastructure.

Today, China’s hydro-ecological management faces dual conditions: urgent issues such as disaster mitigation and pollution control, and the long-term goal of constructing a Beautiful China. Central to this challenge is the critical shortage of “four capacities” of hydro-ecological infrastructure: weak safety capacity leaves us exposed to floods and droughts; low environmental capacity worsens the pollution crisis; degraded ecological capacity drains vitality from water systems; and poor social capacity disconnects people from water, hindering efforts to improve public well-being.

2 Problem Analysis: Understanding the Crisis Through the Lens of the Four Capacities

2.1 Weak Safety Capacity: Fragile Water Security Systems

Safety capacity of hydro-ecological infrastructure refers to its ability and resilience in managing floods and droughts. China’s

monsoon climate triggers cycles of hydrological extremes. A healthy water ecosystem requires adequate space for storage and regulation to cope with both extreme rainfall and droughts. Yet for decades, reliance on engineered solutions, such as levees, concrete riverbanks, and reservoirs, has narrowed floodplains and diminished rivers’ natural adaptive capacity.

Over the past decades, in the pursuit of arable and construction land, floodplains, and rivers have been filled or reclaimed, drastically reducing wetlands and flood storage spaces. As a result, even with unchanged rainfall patterns, flood risks have intensified today. In cities, conventional rapid drainage approaches worsen stormwater issues, leading to rain-induced flooding and prolonged drought. A paradigm shift is urgently needed toward rewilding rivers, restoring space for water to flow, to infiltrate, and to be stored, while harnessing nature’s resilience against climatic extremes.

2.2 Low Environmental Capacity: Intertwined Water Pollution and Scarcity

Environmental capacity of hydro-ecological infrastructure denotes its ability and resilience to tolerate and recover from pollution. Water scarcity has long been a constraint on China’s development, and reduced water availability has further intensified pollution. Shrinking river flows concentrate contaminants, turning rivers into stagnant, degraded water bodies and further impacting groundwater quality.

Large-scale reservoirs and inter-basin transfers have been used to alleviate water shortages and dilute pollution, but such solutions

are costly and unsustainable. Projects like the South-to-North Water Diversion Project relieve urban supply pressures but fail to address the root scarcity and may even pose new risks to the ecosystem safety and health.

Meanwhile, excessive groundwater extraction leads to continuous declines in water tables, vanishing rivers, lakes, and wetlands, and land subsidence, indicating that the current supply-driven model is ineffective in the long term. A shift toward integrated water resource management is essential. This includes enhanced rainwater harvesting and urban wastewater recycling to increase environmental capacity to support long-term sustainability.

2.3 Degraded Ecological Capacity: Over-Engineered Rivers Losing Vitality

Ecological capacity reflects the ability and resilience of hydro-ecological infrastructure to sustain biodiversity and perform ecosystem services. Rivers are living ecosystems, not just drainage channels. Conventional water management, focused on flood control and flow regulation, has straightened rivers, hardened banks, and forced flows into rigid channels.

A series of engineered interventions has severely compromised the ecological functions of rivers, reducing diverse aquatic habitats, and wetlands. Accelerated flows and disrupted connectivity hinder fish migration and plant rooting, causing a sharp decline in biodiversity and the near-collapse of natural purification processes. As a result, rivers have become lifeless drainage channels rather than vibrant ecological corridors.

Restoring the ecological capacity of hydro-ecological infrastructure requires returning rivers to their natural state—enabling them to flow freely and rewilding their ecosystems. This involves reducing concrete embankments, reintroducing meanders, floodplains, mudflats, and vegetated buffers, and enhancing interactions between water, soil, and air to support self-restoration of rivers. Only then can water regain vitality, becoming the ecological lifeblood of cities and countryside. This is also the foundation of river ethics.

2.4 Poor Social Capacity: Fragmented Water Ecologies and a Growing Disconnection Between People and Water

Social capacity refers to the hydro-ecological infrastructure's ability and resilience to support social and cultural services. Water is not only essential for life and production, but also a symbol and cultural medium—a link between people and nature. Yet conventional water management often prioritizes flood control,

water supply, and quality improvement, while neglecting water's social values—its role in daily life, landscape aesthetics, and cultural heritage.

Where water bodies are enclosed and polluted, and riverbanks are hardened, urban waterways become monotonous, inaccessible, and in some cases, unsafe spaces. In the past, people worked, rested, and gathered by the river—but today, embankments keep them apart. Even where new waterfront parks have been built, rigid designs and poor accessibility often fail to attract people to linger and engage.

We must rethink the human–water relationship and reintegrate water into daily life. Waterfront spaces should be key elements of both urban and rural environments, offering ecological, recreational, cultural, and aesthetic values. Only when people can access, approach, and enjoy water can it become a true companion—no longer a force to be controlled or feared.

3 Vision: Building Hydro-Ecological Infrastructure for a Beautiful China

The vision of a Beautiful China is not merely an environmental goal—it represents a fundamental transformation in national development strategies. As a core element of the territorial ecosystem, water ecology plays a vital role in the construction of ecological civilization. In the face of global climate change, ecosystem degradation, and rapid urbanization, we must treat water ecology as a driving force. Guided by the concept of “four capacities,” we aim to enhance hydro-ecological infrastructure systematically and realize the vision of harmonious coexistence between people and water.

Achieving this vision requires an integrated approach to urban and rural water systems, restoring the integrity of aquatic ecosystems and building blue–green networks. Water should become the ecological lifeblood, the soul of cities, and the foundation of rural revitalization. By optimizing spatial layouts at the watershed scale, promoting sustainable use of water resources, and enhancing the carrying capacity of water environments, we can revitalize waterfront spaces and transform lucid waters and lush mountains into invaluable assets—meeting people's growing aspirations for a better life.

4 Integrated Strategies: Four Key Approaches Based on the “Four Capacities”

In response to the current challenges of hydro-ecological governance, we must systematically enhance the “four capacities”

of hydro-ecological infrastructure. For a holistic governance of watershed, this means constructing a sponge system for the entire territory. The following four strategies represent critical points of breakthrough.

4.1 Building Blue–Green Infrastructure to Expand Safety Capacity

We must restore the continuity and integrity of rivers, lakes, and wetland ecosystems. This requires a shift from rigid, large-scale flood defenses to a more precise, localized protection strategy—thus significantly enhancing the safety capacity. Ancient wisdom from the Yellow River and Yangtze River basins, such as the design of enclosures and the elevated mounds, offers valuable lessons for today’s localized, adaptive strategies. Ultimately, solving water safety challenges depends on optimizing land use patterns. Instead of battling against water, we should build a sponge watershed and territorial system.

Modern China has transitioned from an agricultural to a post-industrial society, with the primary industry (agriculture, forestry, animal husbandry, and fisheries) now accounting for only about 7% of GDP. In this context, allowing seasonal inundation of selected farmland, under the premise of ensuring public safety, will not pose a major threat to the national economy. This opens a historic opportunity: through strategic population relocation and high-standard settlement planning, we can designate floodplains with adequate space for water, a goal that is both necessary and attainable.

Equally important is the restoration and protection of widely-scattered traditional small-scale water infrastructure—such as paddy pondscapes, low weirs in streams, and village ponds. China’s vast network of traditional pondscape systems is rapidly disappearing^[1]. Restoring and protecting these distributed “cells” of the sponge landscapes can greatly improve flood and drought resilience, thus bolstering the overall safety capacity.

By channeling the water infrastructure funding more wisely and systematically—through ecological restoration rather than via conventional grey infrastructure—we could, without increasing total expenditures, build a sustainable national-scale sponge system that benefits generations to come.

4.2 Creating a Dispersed Water Cycle System to Expand Environmental Capacity

By capturing rainfall where it falls and allowing it to infiltrate into the soil and recharge groundwater, we create the basic units of nationwide sponge landscapes—often referred to as “sponge

soil” and “green water.” These components are the foundation of terrestrial ecosystems and the micro-scale drivers of a healthy global water cycle. In this regard, China’s 5,000-year heritage of adapting to monsoon climates offers a wealth of experience. Nature-based small-scale water projects, like terraced fields, pondscapes, and low weirs, can be used to effectively build sponge landscapes. Successful ecological restoration efforts in the Loess Plateau provide compelling models for this work. Such sponge systems continuously feed clean water into rivers, offering a truly sustainable water source.

Nature-based urban wastewater recycling and reuse systems are also important. These systems can substantially enhance the environmental capacity by reducing dependence on inter-basin water transfers, stabilizing ecological base flows, and ensuring long-term water quality and quantity. In turn, this lays the foundation for a vibrant blue–green landscape across urban and rural regions.

4.3 Restoring Ecological Resilience to Expand Ecological Capacity

To restore ecological resilience in water systems, we must shift from rigid engineering to flexible, nature-based restoration—reducing human intervention and enabling self-restoration processes. Traditional hard embankments disrupt the ecological interaction between water and the surrounding environment. These should be gradually removed and replaced with ecological slopes, planted with waterlogging-tolerant vegetation that stabilizes banks and purifies water.

Restoring mudflats and ecological buffer zones helps intercept pollutants and improve aquatic habitats. When combined with wetland and eco-park construction, these strategies enhance both ecological function and livability. Measures such as aquatic-life-friendly river design, optimized underwater topography, and the introduction of ecological substrates can promote biodiversity recovery and strengthen the ecological capacity of hydro-ecological infrastructure.

4.4 Creating Waterfront Spaces to Expand Social Capacity

Industrialization and urbanization have increasingly separated people from water, making it urgent to rebuild integrated urban–rural waterfront spaces that reintegrate water into daily life and reestablish the deep bond between people and water.

This can be achieved by developing slow-traffic networks that link rivers, lakes, wetlands, parks, and cultural areas—transforming waterfronts into vibrant spaces for socializing,

recreation, and exercise. Design should embrace natural elements such as terraced revetments, floating wetlands, and accessible platforms, complemented by shading, seating, and lighting, all help create comfortable, inviting environments. Revitalized waterfronts can also incorporate ecological restoration through wetland parks, water forests, and water-themed events—strengthening community cohesion.

Reviving water culture is of equal importance. Restoring historical elements like old docks, stone bridges, and wells adds local character to the water landscapes and reconnects people with the cultural legacy of water. By optimizing waterfront environments and making water a tangible, experiential part of public space, we can create healthy and beautiful rivers for all.

5 Conclusions

Centering hydro-ecological infrastructure on the “four capacities” provides a scientific and actionable roadmap for building a Beautiful China. In the context of climate change, ecological degradation, and water crises, we must move beyond rigid, conventional water management models and embrace nature-based solutions to build resilient landscapes. Through strategies like making room for water, promoting decentralized infiltration and storage, softening hard infrastructure, and reviving human–water relationships, we can systematically enhance the safety, environmental, ecological, and social capacities of hydro-ecological infrastructure—laying the foundation for long-term human–water coexistence. This transformation requires not only technical innovation, but also shifts in governance, administrative functions, and public mindset.

NOTE

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REFERENCE

- [1] Yu, K., Jiang, Q., Wang, Z., & Li, M. (2015). The research progress and prospect of Bei Tang landscape. *Areal Research and Development*, 34(3), 131–136.

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以“四个容量”为核心，构建美丽中国的水生态基础设施

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1 引言

水是生命之源，是生态系统的血脉，更是美丽中国建设的核心支撑。在全球气候变化加剧、涉水灾害风险日益严峻、生态环境承载力逐渐逼近极限的背景下，亟需重新审视水生态系统的调节与支撑能力，反思过去单一、刚性的治水模式，回归自然、顺应生态，建立具有韧性的水生态基础设施。

当前中国的水生态治理既要立足现实的减灾治污问题，又要着眼美丽中国建设的未来目标。我们面临的核心挑战可归结为水生态基础设施“四个容量”的严重不足——安全容量的缺失让我们在旱涝之间疲于应对，环境容量的不足加剧了污染困境，生态容量的丧失让水系失去了活力，而社会容量的短板则让水生态与人的需求脱节，难以真正惠及民生。

2 问题分析：基于“四个容量”认识当前水生态治理困境

2.1 安全容量困境：水安全体系脆弱，治水方式亟待变革

水生态基础设施的安全容量指其调节旱涝灾害的能力和韧性。中国的季风气候决定了水旱灾害的周期性交替。健康的水生态系统必须具备充足的调蓄空间，以应对极端降水和长期干旱的双重挑战。然而，以往的治水实践长期依赖堤坝、硬质护岸和水库等工程措施，大量侵占河湖

的自然调蓄空间，使得河流变得狭窄、刚硬，失去了顺应自然、调节洪水的能力。

过去百余年，我们为追求耕地和建设用地，将河漫滩填筑、湖泊围垦，使得湿地消失、洪水调蓄空间大幅缩减。如今，即使降水强度未变，洪水灾害的风险也显著增加。城市中，传统的“快速排水”模式加剧了雨洪问题，导致“逢雨必涝、久旱成灾”。如何让河流再野化，使水有足够的空间流动、渗透、积蓄，以及如何通过自然的韧性应对极端气候，成为当前治水变革的关键。

2.2 环境容量不足：水污染与水短缺问题相互交织，水质恶化趋势亟待逆转

水生态基础设施的环境容量指其承受水污染的能力和韧性。水资源短缺早已成为中国发展的瓶颈，而水量减少则直接加剧了水污染问题。许多河流因为断流导致污染物浓度升高，水体成为黑臭“死水”，并进一步恶化地下水水质。

目前，许多地区仍依赖大规模的水库调蓄和跨流域调水来缓解水资源短缺，并试图通过这些工程措施稀释污染。然而，这种方式成本高昂，且无法从根本上解决问题。例如，南水北调工程虽然部分缓解了北方城市的供水危机，但并不能改变水资源本身的稀缺性，甚至可能对原生态系统的安全和健康构成潜在威胁。

与此同时，过度开采地下水导致水位持续下降，河湖湿地逐步干

涸，甚至引发地面沉降等次生灾害。这种“拼水量、调水源”的模式已难以为继。我们必须摒弃传统的单一供水方式，转向水资源循环管理模式，提升雨水收集与利用能力，充分开发城镇的再生水资源，增加水环境容量，实现水资源的可持续利用。

2.3 生态容量堪忧：河流被过度工程化，水系失去生命活力

水生态基础设施的生态容量指其承载生命和生态功能的能力和韧性。河流不是简单的排水沟渠，而是一个充满生命力的生态系统。然而，传统的治水方式往往以控制洪水、管理水量为目标，采用硬质河岸、混凝土渠道，将蜿蜒的河流截弯取直，迫使水体以单一模式流动。

一系列的工程化改造极大破坏了河流的生态功能。原本多样化的水生生态被抹平甚至完全消失，湿地和滩涂面积显著缩减；水流过快，河流连续性受阻，鱼类无法洄游，水生植物无法扎根，生物多样性骤降，水系的自净能力几近丧失。最终，河流不再是充满生机的生态纽带，而成为毫无生机的排水管道。

要恢复水生态基础设施的生态容量，必须让河流回归自然——恢复其自由流淌的权利，并再野化。例如，减少水泥护岸，恢复蜿蜒河道、洪泛区、滩涂与植被缓冲带，增加水体与土壤、空气的自然交互，提升河流的自我修复能力。唯有如此，水才能焕发生命，城市和乡村才能真正拥有灵动的“生态血脉”。这也正是河流伦理的基础。

2.4 社会容量缺乏：水生态被割裂，人与水的联系日益疏远

水生态基础设施的社会容量指其承载社会和文化服务的能力和韧性。水不仅是生命之源、生产资料，更是文化的载体和象征，是人与自然共生的纽带。然而，传统的水治理模式更关注于防洪、供水和水质达标，而忽视了水的社会价值，即水对人类生活、景观美学及文化遗产的重要作用。

当水体被围困、污染，水岸被硬化改造，城市中的水系就变成了单调、不可亲近的存在，甚至成为“死亡陷阱”。过去，人们在河边劳作、休憩、聚会，如今却被大堤隔离。即使一些地区新建了滨水公园，也因设计僵化、亲水性不足，难以真正吸引人们驻足。

我们需要重新思考人与水的关系，让水系真正融入人们的生活。滨水空间应成为城市与乡村的重要组成部分，具备生态、游憩、文化和审美启智等多重功能，使居民可以亲水、近水、享水，让水真正成为人类的朋友，而非被束缚、被隔离的“野兽”。

3 目标愿景：打造美丽中国的水生态基础设施

美丽中国的愿景不仅是环境保护的目标，更是一项关乎国家发展方式转型的系统工程。水生态作为国土生态系统的核心要素，在生态文明

建设中发挥着关键作用。面对全球气候变化、生态系统退化和城市化进程加快等挑战，我们必须以水生态为核心驱动力，以“四个容量”为统领，推动水生态基础设施的系统性提升，实现人与水和谐共生的美丽中国愿景。

要实现这一目标，需要统筹城乡水系统建设，恢复水生态系统的完整性，构建蓝道与绿道网络，让水成为生态之脉、城市之魂、乡村振兴之基。通过科学优化流域空间格局、促进水资源的可持续利用、提升水环境承载能力，我们能够激活城乡滨水空间，使绿水青山真正转化为金山银山，满足人民对美好生活的迫切需求。

4 综合治理策略：以“四个容量”为基础的四大策略

面对当下水生态治理的挑战，我们需要系统性提升水生态基础设施的“四个容量”，从流域整体治理的角度出发，构建全流域的国土海绵系统。以下四项策略是关键突破点。

4.1 降堤破圩，构建蓝绿交织的水生态基础设施，扩大安全容量

恢复河流、湖泊和湿地生态系统的连续性与完整性，转变传统治水模式，从全面设防走向局部精准保护，显著提升安全容量。黄河流域和长江流域千百年的水适应智慧（如围、墩等设计），可为我们今天的局地精准保护策略提供借鉴。水安全问题的根本解决之道在于陆地空间的优化，应打破“人水相争”的治理模式，建立海绵化的流域和国土体系。

当今中国已从传统农业社会迈入后工业时代，第一产业（农林牧渔业）占GDP的比重已降至7%左右。在保障人民生命财产安全的前提下，破圩让部分农田的季节性淹没已不再对国民经济造成重大影响。因此，应抓住城镇化发展的历史性机遇，通过人口合理疏解与安置，科学优化洪泛区布局，高标准设计聚落的局地水安全空间，为洪水留足空间，这并非奢求。

同时，必须恢复并保护分布广泛的传统小型水利设施，如农田陂塘、溪流低堰、村镇池塘水系等。中国大地上分布的传统陂塘系统正在大量消失^[1]。通过修复和保护这些国土海绵的“细胞单元”，可显著提升旱涝应对能力和整体安全容量。

若能将现有可观的水利工程资金更智慧、更系统地投向生态空间的修复与重建，避免传统的灰色水利思维，无需增加国家整体投入，亦可构建可持续、能长久造福后代的国土海绵系统。

4.2 分散渗蓄，构建分散式渗蓄和水循环系统，增加环境容量

源头分散渗蓄，让降雨就地渗透，进入土壤、补充地下水，可形成海绵国土的基本单元，也被称为“土壤海绵”和“绿水”。它们是国土

生态系统生机勃勃的根本所在，也是维护地球水循环健康的微观基础。在这方面，中国五千年应对季风气候的智慧提供了丰富的经验。通过基于自然的小型水利工程——如梯田、陂塘、低堰等——可有效构建海绵国土。中国黄土高原的生态修复成功案例为海绵地球的建设提供了重要启示。这类国土海绵能够为河流提供源源不断的清流，这才是真正的不竭水源。

同样重要的是，基于自然的城镇污水再生和循环利用体系，可大幅提升河流的环境容量，减少对跨流域调水的依赖，稳定补给河流生态基流，保障水质与水量的可持续性，最终构建起蓝绿交织、清新明亮的城乡水生态景观。

4.3 去硬还生，恢复水系生态韧性，提高生态容量

恢复河流的生态韧性，需从“刚性治理”向“柔性修复”转变，减少人为干预，让水系具备自我修复的能力。传统的硬质护岸破坏了水体与周边环境的生态交互空间，应逐步拆除并改造为生态缓坡，同时种植耐水植物，以稳固河岸、净化水质。

恢复滩涂和生态缓冲带，不仅能拦截污染，还能增强水生生境质量。结合湿地与生态公园建设，还可将生态修复与人居环境提升相融合。通过构建水生生物友好型河流、优化水下地形、引入生态基质，有助于生物多样性恢复，提升水生态基础设施的生态容量。

4.4 与水为友，打造亲水空间，提升社会容量

工业化和城市化进程使得水系与日常生活日益脱节，亟需重建城乡一体的亲水空间，让水融入人们的日常生活，重新建立人与水的深度联系。

通过建设滨水慢行网络，连接河湖湿地、公园和文化区，可将水岸转化为社交、休闲和健身的重要空间，提升其可达性。亲水设施应采用自然化设计，如阶梯驳岸、生态浮岛和亲水平台，并配套遮阴、座椅、照明等设施，提高舒适度与使用率。水岸空间的活化也可与生态修复相结合，打造湿地公园、水上森林，并开展水上活动和文化节庆等，增强社区凝聚力。

水文化的复兴也应融入滨水空间设计，恢复古码头、石桥、水井等历史要素，打造富有地域特色的水文化景观，让人们重新感受水的历史与文化魅力。优化水岸环境，使水成为可触可感的公共场所，营造“幸福河流”“美丽河流”。

5 结语

以“四个容量”为核心的水生态基础设施构建为美丽中国建设提供了科学路径和实践指南。面对气候变化、生态退化和水资源危机，我们

必须摒弃传统的刚性治水模式，转向基于自然的解决方案，构建韧性国土。通过降堤破圩、分散渗蓄、去硬还生和与水为友等举措，我们能够系统性地提升水生态基础设施的安全容量、环境容量、生态容量和社会容量，实现人与水的和谐共生。要实现上述治水理念的变革，不仅需要技术和规范的改进，更需要行政职能的调整及观念的革新。

注

本文根据作者2025年2月28日在水利部科学技术委员会全体会议上的专题发言整理而成。