



ASIAN INFRASTRUCTURE
INVESTMENT BANK

ASIAN INFRASTRUCTURE FINANCE 2026

WHERE THE WATER FLOWS

Infrastructure and Governance
for a Sustainable Water Cycle



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About the Cover: The cover depicts a misty, mountainous river landscape where a small boat navigates the water, illustrating the seamless movement of water and moisture between the earth, air and open waterways. This scene highlights the interdependence of nature, human and the water cycle.



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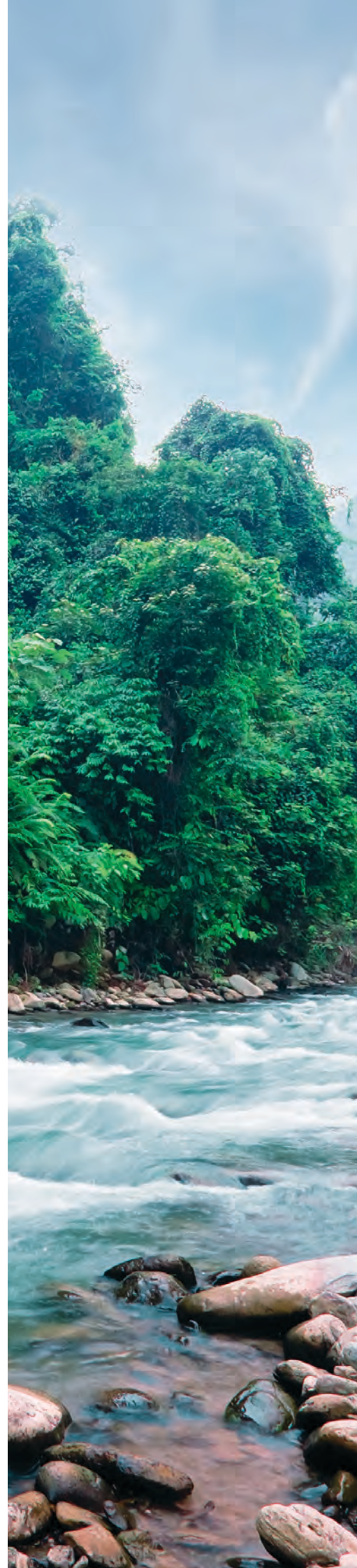
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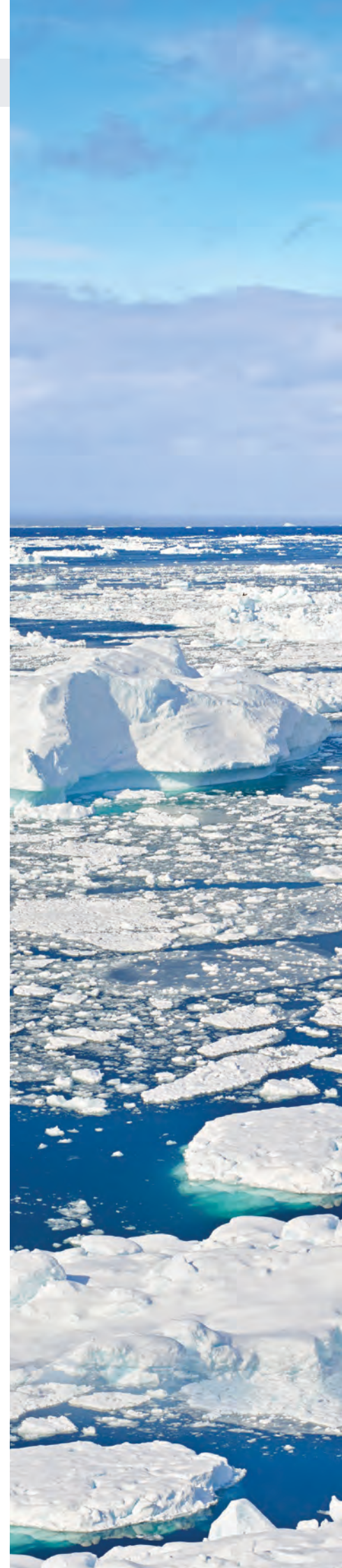
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ABBREVIATIONS

AIB	Asian Infrastructure Investment Bank
BCM	billion cubic meters
BII	Biodiversity Intactness Index
EPI	Environmental Performance Index
FAO	Food and Agriculture Organization
IEA	international environmental agreement
IFI	international financial institution
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
GDP	gross domestic product
GLOF	glacial lake outburst flood
HIC	high-income country
HKH	Hindu Kush Himalaya
LAI	leaf area index
LIC	low-income country
LMIC	lower-middle-income country
MDB	multilateral development bank
MRIO	multi-regional input-output
NbS	nature-based solution
ODA	official development assistance
PES	payments for ecosystem services
SDGs	Sustainable Development Goals
SIMURP	Strategic Irrigation Modernization and Urgent Rehabilitation Project
UMIC	upper middle-income country
UN	United Nations
VWT	virtual water trade
WUG	water user group

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FOREWORD

From the great river basins of Asia to the cities and economies they sustain, and to the global systems they are part of, water has shaped where and how communities take root. It remains fundamental to life, livelihoods and development, sustaining economic activity across societies. Yet as pressures on water systems intensify, what has often been managed as a sectoral issue is emerging as a broader constraint on growth and resilience.

As *Asian Infrastructure Finance 2026: Where the Water Flows* shows, this shift reflects a more fundamental reality: The global water cycle itself functions as essential infrastructure. It stores, moves and regulates water across landscapes and borders, supporting food and energy systems and shaping the reliability of the economies that depend on them. Global moisture flows, which we can think of as flying rivers, also show the interconnectedness of water between regions. When this system is disrupted—through climate change, environmental degradation or weak governance—the consequences extend far beyond water, affecting economic stability and development prospects.

These pressures are already evident across Asia and various regions. Climate change is altering rainfall patterns and water availability. Rapid urbanization and changing land use are placing additional strain on water systems that are already under stress. The result is greater volatility—more frequent and more severe floods, droughts and water-quality challenges. For many economies, this is no longer a distant risk but a present and growing constraint.

Yet investment approaches have not kept pace with the nature of the challenge. Water is still too often addressed through discrete projects, while the underlying systems—basins, networks and the interaction between built and natural infrastructure—remain fragmented. The gap is not only one of financing, but of turning need into projects that are coherent, scalable and investable.

For multilateral development banks, this is a central challenge. At AIIB, we work with our members to support infrastructure that is sustainable, climate-resilient and fit for a changing world. This includes strengthening project preparation, improving coordination across sectors and institutions, and helping create the conditions for private capital to contribute more effectively. It also requires recognizing that resilience depends as much on natural systems as on engineered solutions.

This report makes a timely contribution by reframing how water is understood in the context of infrastructure and investment. It highlights where current approaches fall short and where opportunities lie. More broadly, it underscores a simple point: As water risks become more visible, the cost of inaction will rise—but with a more integrated approach, water can also be a source of stability and long-term value.

I hope this report will help advance that effort and support more coordinated action across sectors and borders.



Zou Jiayi
President and Chair of Board of Directors
Asian Infrastructure Investment Bank

PREFACE

Water makes up the circulatory system of nature—it reaches and regulates all the major components of Earth. Despite its importance, we have historically viewed water through a fragmented lens: as a resource to be extracted, a hazard to be managed or a service to be delivered through pipes and pumps. *Where the Water Flows* invites the reader to adopt a broader and deeper perspective and to view the global water cycle itself as natural infrastructure.

The concept of water infrastructure typically conjures up images of dams, levees and aqueducts—the grey engineered concrete built to control water’s flow. While these structures are vital, the planetary water cycle, driven by the sun’s energy and governed by the complex processes of Earth itself, is the original and most critical infrastructure upon which all life—and all human activity—depends.

This natural infrastructure performs a range of indispensable functions. It is a powerful environmental pump, with forests transpiring moisture and replenishing giant atmospheric rivers of freshwater. It is a global thermostat, regulating climate through evaporation and cloud formation. It is a giant filter, as water percolates through the soils and wetlands, emerging purified. It is, in essence, the planet’s own life-support system.

Why frame the water cycle in these terms? Because language shapes perception and perception drives action. By recognizing the water cycle as critical infrastructure, we fundamentally alter its place in economic and political decision-making. We begin to ask essential questions: What is the replacement cost of this natural system? What are the risks of its degradation? How do we invest in its maintenance and make it more resilient?

The answers are sobering. Our collective actions—clearing forests, draining wetlands, emitting greenhouse gases—are inadvertently dismantling this very infrastructure. We are altering the delicate balance of evaporation, condensation and flow that has sustained stable climates and water availability for millennia. The result is a less predictable, more volatile water cycle, manifesting itself in more extreme floods and severe droughts.

The problem is, at least in part, one of governance. The global water cycle is a complex nesting of closely interlinked blue and green water cycles at local, regional and global levels. For example, the report’s analysis suggests that Ramsar designation is associated with better outcomes in smaller wetlands and in countries with stronger environmental and water-governance capacity, while effects are weaker in larger wetlands and in countries with weaker governance capacities. Governance also does not work well when natural assets span multiple jurisdictions. The result is the four-dimensional global water crisis: “too much, too little, too dirty, too variable.”



Erik Berglof
Chief Economist
Asian Infrastructure Investment Bank

This report aims to provide an overview of the global water cycle as natural infrastructure. We explore its key components and examine the devastating and often invisible ways it is being altered by human activity. Most importantly, we will lay the groundwork for a new framework of governance and investment—one that recognizes that our long-term water security depends not only on the pipes in the ground but on the health of the sky, the forests and the soil.

As you will read, the tools to monitor this system, from isotopic analyses that trace a water molecule's journey, to satellites that map global moisture flows, have never been more powerful. The challenge now lies in using that knowledge to manage, protect, restore and make more resilient the planet's most essential asset. The constraint is no longer the knowledge and tools of measurement but our imagination of how to use them.

For a development bank focused on infrastructure, this means thinking in systems and landscapes instead of individual sectors. Water is not a sector or isolated project. It implies linking up blue water and green water interventions—and inland water and the oceans—and recognizing that these must be addressed together. Urban water projects must be combined with efforts to improve watershed management and coastal water infrastructure with inland measures.

The skeptics of nature as infrastructure point to the difficulties in mobilizing private and institutional capital when there are no identifiable revenue streams from nature assets and limited mechanisms for financing them. This may be true for some natural assets, but it does not hold for water, where the private sector is already heavily invested and owners of water resources are accustomed to charging for their services.

One common message emerges: Keep water, as much as possible, in nature, from healthy well-governed wetlands to flourishing forests, using responsible irrigation and restoring natural assets upstream. These "reservoirs" will help relieve water stress and prevent harmful runoffs into rivers and oceans. Developments in science and improved data are transforming our ability to improve their governance and mobilize financial resources. We now urgently need scientists, policymakers and the financial world to come together to safeguard our critical global life-support system.



EXECUTIVE SUMMARY

Water underpins biodiversity and ecological resilience, economic performance and social stability, and yet it is rarely understood and managed as the interconnected system it is. At the global scale, water is a holistic system, flowing through the atmosphere, soils, rivers, wetlands, aquifers and glaciers. Global water cycles connect infrastructure, land use and governance decisions across borders and sectors. At a regional level, water is transboundary, with microclimates and any associated disruptions affecting whole regions. Water is also a local issue, where the availability of water often exerts a strong impact on livelihoods. Economic activity, on the other hand, puts pressure on local and regional water systems.

Climate change is now destabilizing this hydrological cycle, amplifying floods, droughts and water-quality shocks while increasing uncertainty around water availability. These shifts will have profound regional and local impacts. This report, *Where the Water Flows*, advances a central proposition of direct relevance to government ministries, planning agencies and multilateral development banks: The hydrological cycle itself functions as infrastructure. It delivers essential services on which economies depend, including flow regulation, storage, water supply, energy generation, food production and risk reduction. Water in the natural environment is also key to sustaining biodiversity and other natural capital; any water risk is an environmental and biodiversity risk. When degraded or fragmented, it becomes a source of cascading risk; when protected and managed, it becomes a foundation for resilience and growth. The first key message of the report is that the water cycle, itself a key infrastructure for humanity, must be protected.

Rising temperatures, ecosystem degradation and shifting rainfall patterns are weakening the natural systems that regulate water flows and quality. As a result, conventional infrastructure—much of which is designed for historical hydrological conditions—is increasingly exposed to variability, sedimentation and shock.

The report is also about adaptation. Many examples illustrate how climate adaptation is bolstered by investments that integrate engineered assets with natural systems—healthy catchments, wetlands, floodplains, soils—thereby reducing physical risk, improving infrastructure reliability and delivering multiple economic and social benefits. These approaches can complement traditional infrastructure and are particularly valuable when climate uncertainty is high.

Governance across all levels remains essential. Effective governance, robust data and adequate finance are crucial to realizing the integration of grey infrastructure with natural systems. Strong institutions are needed to manage trade-offs across sectors, jurisdictions and time horizons, while modern data and forecasting systems are essential for risk-based planning and operation. Financing remains critical. Public resources alone

will not be sufficient to scale resilience, particularly for nature-based and system-level investments whose benefits accrue over time and across stakeholders. Public risk-sharing mechanisms, targeted guarantees and long-term private capital—aligned with resilience outcomes—will be essential.

The findings of this report point to a strategic shift away from fragmented water responses toward systemic water resilience. The recommendations that follow summarize the core actions required to operationalize this shift, with expanded recommendations set out in the conclusion.

1. Invest Across Water Systems

Climate adaptation requires investment across water systems, combining natural and engineered infrastructure. Keeping water in the landscape is central to the performance of resilient infrastructure.

2. Scale Infrastructure for Climate Adaptation

Intensifying floods, droughts, landslides and sea-level rise make adaptation infrastructure unavoidable. Engineered systems must be designed to adapt to changing hydrology and integrated with natural systems to protect vulnerable communities.

3. Reform Water Governance for Tomorrow

Rising water variability demands governance. Water must be managed when increasingly too much, too little, too dirty and too unequal. Rules and institutions should align with basin hydrology and transboundary realities.

4. Advance Equity and Inclusive Water Systems

Water risks fall disproportionately on vulnerable groups. Equity, gender and inclusion must be embedded in water planning, infrastructure investment and governance.

5. Leverage Technology-Enabled Infrastructure

Resilient water systems depend on reliable data and forecasting. Investment in hydrometeorological networks, early warning and decision-support systems is essential.

6. Mobilize Finance for Resilience

Water investment gaps are growing. Scaling resilience will require public risk-sharing, targeted guarantees and long-term private capital aligned with adaptation outcomes.



CHAPTER 1 OVERVIEW

1.1 Objective and Context

Water connects every living system on the planet. At a global level, it moves through air, soil, glaciers, wetlands, rivers, lakes and oceans, sustaining ecosystems, economies, and societies. These interconnected stocks and flows form the global water cycle, and its system stability ultimately determines the reliability of infrastructure, food production, and economic activity. This interconnectedness gives water the characteristics of a global public good, yet one that is often fragmented by governance and infrastructure development. Water is often treated as a local resource, even though it functions as a system of stores (glaciers, soils, wetlands, aquifers) and flows (rivers, atmospheric moisture corridors, runoff, groundwater recharge).

The *Asian Infrastructure Finance (AIF) 2026* report, *Where the Water Flows*, examines this global hydrological cycle (including water overground and underground) as a form of natural infrastructure, one that is increasingly destabilized by climate change, deforestation, land degradation, and shifting rainfall patterns. The report considers how these changes affect water security, food security, and economic performance.

As temperatures rise and ecosystems degrade, the global water cycle has become more volatile. For many countries, this means more frequent

droughts, more intense floods, greater water-quality shocks, and greater exposure to water stress. But it also creates opportunities to invest in natural, engineered, and institutional infrastructure that works with, rather than against, the water cycle.

These opportunities are of direct relevance to farmers (who depend on rainfall timing, soil moisture, and irrigation performance), hydropower operators (who are affected by sedimentation, flow fluctuations, and catchment condition), water utilities (who face rising treatment costs and contamination pulses), cities (which face flood and heat risks), and finance ministries (for whom water stress influences sovereign ratings).

This is a report about the infrastructure of water itself, rather than the water sector. This report brings these perspectives together, showing how local impacts are tied to global water dynamics. It responds to a growing recognition that water risks are intensifying at the same time as climate change, ecosystem degradation, and rising demand are destabilizing the hydrological cycle. While much of the global water debate has focused on scarcity, governance, or infrastructure separately, this report brings these dimensions together. Its central contribution is to frame the water cycle itself as a form of critical infrastructure. It underscores the inseparable need for investments that protect this common water cycle, and also infrastructure investments to safeguard our water resilience.

1.2 Water as a Global Issue

Global Water Systems as Natural Infrastructure

The hydrological cycle is a dynamic system of water stocks and flows that stabilizes climate, produces rainfall, regulates temperature, supports photosynthesis, shapes landscapes, and underpins food, energy, and water security. The atmosphere holds around 13,000 cubic kilometers of water at any moment but transports more than 500,000 cubic kilometers each year. The soils and wetlands also hold vast volumes, buffering flood peaks and maintaining ecological productivity. Together, glaciers, snowpack, and aquifers function as water towers, releasing water seasonally and sustaining base flows in major river systems across Asia and beyond.

These systems provide important ecosystem services, including nutrient cycling, disease regulation, carbon storage, water purification, biodiversity support, energy production, and recreational and spiritual values. Yet their functions are vulnerable and can quickly collapse. Failures in one location can cascade through space and time: Seemingly small pressures can trigger disproportionate hydrological change.

A Cycle Under Pressure

Rising temperatures alter evaporation, moisture recycling, and rainfall distribution. Land degradation and deforestation are weakening feedback loops that sustain evapotranspiration and moisture recycling, while the loss of wetlands and soil moisture is reducing the landscape's capacity to regulate water flows. Rivers and lakes face over-extraction and pollution. Glaciers in the Hindu Kush Himalaya, the largest store of ice outside the polar regions, are projected to lose between one-third and two-thirds of their mass this century, threatening dry-season water security for close to two billion people downstream.

These disruptions weaken the hydrological cycle's ability to stabilize climate and regulate flows. As natural storage and conveyance systems decline, engineered infrastructure becomes more exposed

to variability, shock, and sedimentation. For people and the planet, this means greater volatility in water supply, more frequent flood and drought extremes, and rising pressure on the systems that support food, energy, and urban resilience.

Flying Rivers and Moisture Interdependence

New analysis undertaken for this report shows that water is profoundly shared and circular. Flying rivers—atmospheric moisture corridors—function as natural aqueducts, transporting water vapor across continents in ways that link distant regions. Nearly half of global land rainfall originates from moisture generated over other land surfaces. No economy is moisture self-sufficient. Landlocked economies in Central Asia receive around 47 percent of their rainfall from foreign moisture sources, far above the global average of 26 percent. Large rainforest nations like Brazil, the Democratic Republic of the Congo, and Indonesia generate roughly one quarter of global transboundary moisture flow despite representing only eight percent of global land area.

These findings underscore that water is a global public good, even when its impacts are experienced regionally or locally. While a farmer may experience only rainfall on her field, that rainfall is connected to distant ecosystems. A hydropower plant may experience only sediment buildup at its reservoir, but that sediment load reflects upstream land-use choices. The cycle is global in its function and yet regional or local in its consequences.

1.3 Water as Infrastructure

Infrastructure both shapes the hydrological cycle and depends on it. The performance of dams, irrigation systems, urban drainage networks, and water supply systems ultimately reflects the condition of the broader water cycle in which they operate. The report's analyses show that investments in natural, engineered, and institutional infrastructure across the cycle can significantly enhance water resilience when aligned with system dynamics. Ultimately, the effectiveness of water infrastructure depends on its ability to harmonize with the hydrological cycle.

Natural Infrastructure

When intact, natural systems can provide infrastructure grade services:

- Forests regulate evapotranspiration, stabilize rainfall, and reduce sediment loads that compromise hydropower production. Cross-country evidence from the report shows that improved upstream forest cover can increase the capacity factor of run-of-river hydropower plants by 13 percent, underscoring the value of catchment restoration.
- Wetlands act as natural filters and flood buffers, absorbing peak flows and moderating the water-quality shocks that often follow major flood events, by filtering sediment, pathogens, and pollutants.
- Soils, grasslands, and riparian corridors slow runoff, holding water in the landscape and supporting both groundwater recharge and agricultural productivity.
- Glaciers and snowpack release water seasonally, sustaining dry season flows. For agriculture and energy, they maintain irrigation and hydropower reliability during peak demand periods.

However, natural infrastructure performs best when their conservation is managed and financed effectively, and when institutions are strong. For example, Ramsar-designated wetlands show improved outcomes only in countries with robust governance and financial capacities.

Engineered Infrastructure

Engineered systems like irrigation canals, hydropower facilities, reservoirs, stormwater systems, and water-quality monitoring networks remain essential to water security. But their performance is linked to the conditions of the natural systems around it, meaning that investments must account for how a changing hydrological cycle alters the risks and conditions under which these systems operate:

- Irrigation delivers highly variable benefits across agroecological zones; the strongest and most resilient outcomes occur when physical rehabilitation is paired with climate-smart

agriculture, water-saving technologies, and diversified cropping systems. Solar-powered irrigation expands access to water and energy, but without appropriate pricing and regulation, it can accelerate groundwater depletion, turning a technological gain into a long-term risk.

- Hydropower infrastructure is similarly sensitive to the landscape in which it is embedded: upstream land-use decisions determine sedimentation rates, flood debris, and flow variability, all of which affect generation capacity and asset longevity.
- Urban drainage and flood-resilience systems function best when integrated with wetlands, permeable surfaces, and other nature-based solutions that can absorb or redirect water more flexibly than concrete alone.

Institutional Infrastructure

Infrastructure effectiveness depends heavily on governance. Governance arrangements, whether basin authorities, municipal utilities, or national regulatory bodies, must increasingly operate in a world of “too much, too little, too dirty, and too unequal” water, where variability is the norm and vulnerability is unevenly distributed.

- Water pricing and tariff structures shape behavior and determine how efficiently water is used.
- Land-use planning can determine pollution risks after floods and influence water-quality shocks.
- Inclusive governance, particularly the involvement of women and marginalized communities, enhances resilience by bringing local knowledge and lived experience into water management decisions.

Institutional capacity shapes outcomes as much as physical investments. This is evident in wetlands management, groundwater regulation, flood response, hydropower performance, and cross-border water cooperation.

1.4 Economic and Policy Implications

Because economies depend on stable water flows, disruptions in the water cycle increasingly translate into economic risk, affecting agricultural productivity, energy generation, urban resilience,

and fiscal stability. The economic implications of water stress are increasingly visible across countries and sectors. As the hydrological cycle becomes more variable, its impacts extend beyond local scarcity to affect sovereign creditworthiness, trade patterns, food security, public health, and the reliability of critical infrastructure. Evidence from this report shows that water risks are now inseparable from broader macroeconomic performance.

- Water stress affects sovereign credit ratings for lower-middle-income economies. A 10-percentage-point increase in water stress reduces ratings by nearly one notch.
- Water scarcity is uneven and worsening, with 31 percent of the global population now living in water-stressed basins and major food-producing regions increasingly exposed.
- Food security is at risk with around one-fifth of global wheat and maize production occurring in basins facing high water stress.
- Trade patterns amplify vulnerability, as virtual water flows are driven by pricing distortions, not resource endowment. Tariff reforms can improve allocation and reduce stress.
- Flood-driven water-quality shocks impose economic costs, increasing treatment expenses for utilities, disrupting agriculture, and straining public-health systems—especially where wetlands and riparian buffers have been degraded.
- Governance determines outcomes: Allocation rules, groundwater regulation and pollution control shape whether infrastructure reduces or compounds risk.
- Water ODA has declined, even as risks increase, creating an opening for MDBs.

These findings show that protecting water systems is essential for economic competitiveness, national security, and financial stability.

1.5 Opportunities for Multilateral Development Banks

For MDBs, strengthening infrastructure resilience increasingly requires investing not only in engineered assets but also in the natural and institutional systems that sustain the water cycle. MDBs can play a critical role in strengthening water resilience across the hydrological cycle. The following

opportunities reflect both the physical reality of where water flows and the economic imperative to ensure that infrastructure and policy interventions work with, rather than against, the water cycle:

Strengthen the Infrastructure of the Hydrological Cycle

MDBs can invest across the hydrological cycle, integrating natural, engineered, and digital infrastructure. This includes maintaining the ecosystems that regulate water, upgrading the built systems that deliver it, and strengthening data, planning tools, and systems.

Build the Institutions that Make Water Systems Work

MDBs can help build the institutional infrastructure that makes water systems function. Pricing and allocation rules, groundwater regulation, pollution control, land-use enforcement, and basin-level coordination determine how water risks are shared or amplified.

Align Economic Incentives with Hydrological Realities

MDBs can support economic and financial reforms that align incentives with hydrological realities and help countries design tariff structures, fiscal policies, and cross-border arrangements that reduce risk, improve efficiency, and strengthen long-term competitiveness.

Mobilize Private Finance for Natural and Hybrid Infrastructure

MDBs can help mobilize private capital for nature-based and hybrid infrastructure. Mechanisms such as Payments for Ecosystem Services, Public-Private Partnerships for Nature (PPPNs), nature credits, and resilience-linked financing can crowd in private investment toward natural infrastructure that delivers measurable infrastructure resilience outcomes.

Flowing Toward a Connected Future

Throughout this report, a simple message flows: Water is shared, circular and critical. The hydrological cycle links people, economies, and ecosystems across borders, sectors, and scales. Its destabilization threatens water security, food security, energy security, and financial stability. But it also reveals opportunities to invest in natural, engineered, and governance infrastructure that strengthens resilience, restores ecosystems, and supports sustainable development.

Where the Water Flows follows the cycle from atmospheric moisture to soils, wetlands, rivers, farms, cities, and coasts, illustrating how each part of the system affects the others, and how infrastructure investments can align with, rather than disrupt, the cycle. Protecting the water cycle and providing water security are not competing objectives but two sides of the same goal: securing the foundation of prosperity for current and future generations.





CHAPTER 2

GLOBAL FRESHWATER AND INFRASTRUCTURE

HIGHLIGHTS

- The freshwater cycle is a global natural infrastructure system whose stability underpins food, energy, climate, and economic security. Human-driven change is destabilizing key water stores and flows, threatening Earth's habitability.
- Ecosystems maintain freshwater flows. In contrast to engineered systems, biodiverse ecosystems can self-regulate, adapt, and evolve in response to change.
- Hydrological, ecological, and social systems are tightly interconnected; shocks such as droughts, floods, and land degradation propagate across sectors and borders, amplifying risk.
- Investing in natural infrastructure and integrated water governance is essential to restore stability, reduce climate risk, and build resilient development pathways.

2.1 Freshwater Outside a Safe Operating Space for Humanity: What is the Role of Infrastructure for Restoring Planetary Safety?

This chapter examines the foundations of the global water cycle, and the infrastructure functions it provides. Understanding these processes can help design infrastructure systems that remain reliable under changing climatic and hydrological conditions.

Freshwater—the bloodstream of the biosphere—provides the fundamental conditions for all life on land, while its circulation also crucially depends on the living ecosystems it sustains. On a global average, roughly 40 to 50 percent of terrestrial precipitation originates from land-based moisture [Tuinenburg et al. (2020); van der Ent et al. (2010)], which is recycled through ecosystem storage and transpiration. This percentage is much higher regionally.

In large parts of Africa, South America, and China, the majority of rainfall is driven by the vapor returned to the atmosphere by ecosystems. Rainfall delivers the water that is the prerequisite for life, from the cell level to ecosystems. Given stable supplies of water, healthy ecosystems deliver a range of ecosystem services, including purifying water, transporting nutrients, and buffering against weather extremes. Around 77 percent of global croplands rely solely on rainfall [FAO (2025)], while croplands equipped for irrigation ultimately depend on rainfall that replenishes lakes, rivers, and aquifers.

The circulation of water that sustains and is sustained by life also regulates Earth's climate system through cloud formation, energy transport, and the regulation of greenhouse gases. Thus, the freshwater cycle can be understood as a global infrastructure system, comprised of many sub-systems nested into each other, that together provide a variety of infrastructure services critical for thriving societies.

However, freshwater is now in an extended planetary crisis. According to WHO and UNICEF (2025), 2.1 billion people lacked safely managed drinking-water services and 3.4 billion lacked safely managed sanitation services in 2024.

At a planetary scale, droughts, flooding, and water pollution have become so widespread that the global water cycle is deemed to now have transgressed the planetary boundary for freshwater (Figure 1), risking permanent departure from the relatively stable environmental conditions that for the past 12,000 years allowed modern civilizations to develop and flourish [Porkka et al. (2024); Richardson et al. (2023); Wang-Erlandsson et al. (2022)]. These water changes are triggering abrupt and persistent ecological shifts, flipping forests into savanna-like states and carbon sinks into carbon sources [Berdugo et al. (2020); Hubau et al. (2020); Staal et al. (2020)].

Reported economic losses from weather-, climate- and water-related hazards have risen sharply over time; Douris et al. (2021) report that losses increased roughly sevenfold from the 1970s to the 2010s, reflecting higher exposure and asset values. Fewer than half of the world's large rivers reach the ocean uninterrupted due to the construction of a variety of engineered infrastructure barriers, such

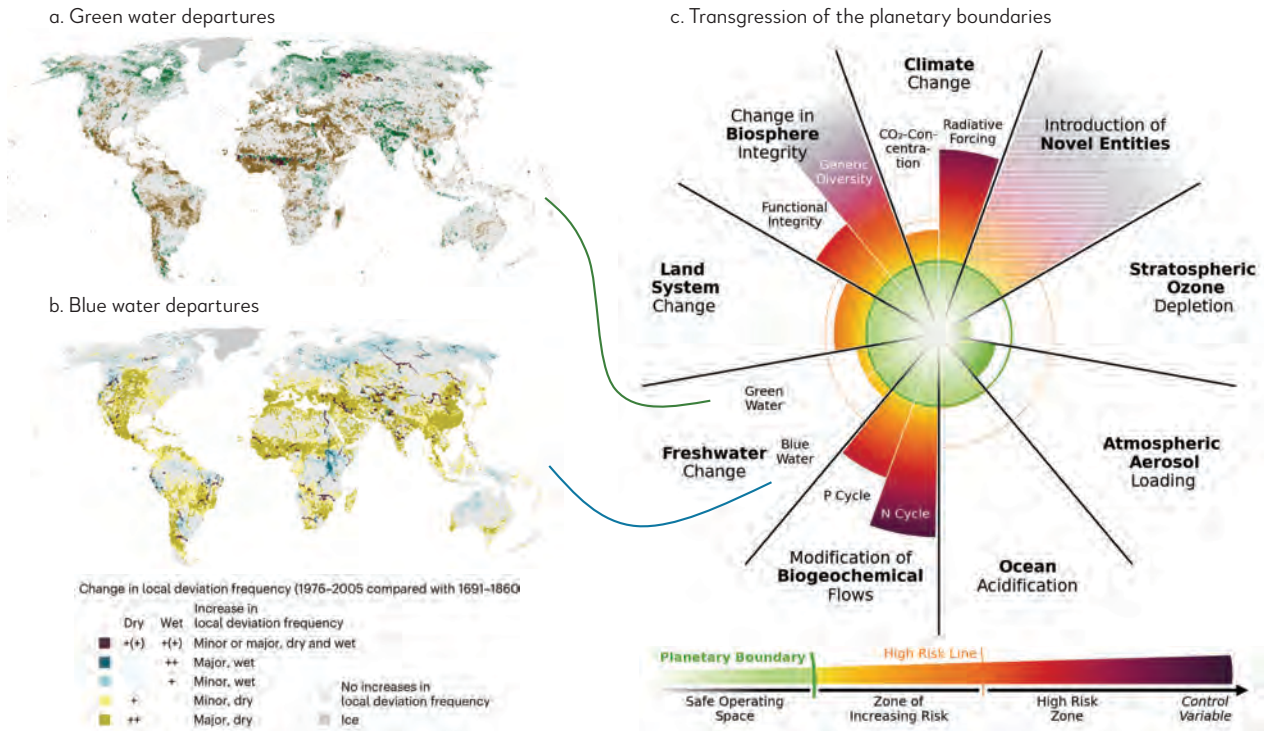
as dams, weirs, culverts, sluices, fords, and ramps [Grill et al. (2019)], which promote coastal erosion and block fish migration. Global irrigation can affect monsoon onset, and groundwater depletion has been shown to shift Earth's rotational pole [Guimberteau et al. (2012); Seo et al. (2025)], while the conversion of natural ecosystems to pastures and croplands over half of Earth's land surface has resulted in an overall reduction in rainfall.

Human activities are not only 'victims' and 'drivers' of the planetary freshwater crisis but can also effectively enhance the functioning of nature as infrastructure. Restoration programs have already shown success in securing or revitalizing water functions, such as revegetation on the Loess Plateau that reduced soil erosion [Bai et al. (2024)], along with structures such as check dams [Zhang et al. (2022)]. In already disturbed anthropogenic landscapes, there are many ways to enhance water functions by mimicking nature. For example, water treatment plants remain critical for protecting the water cycle and aquatic systems, and constructed wetlands are a form of biomimicry that provides both freshwater habitat and cost-efficient water purification.

Integrating trees into agricultural landscapes through agroforestry and silvopasture can increase infiltration, water retention, and groundwater recharge. And planting trees and shrubs along streams and rivers can help prevent erosion and flooding and reduce the pollutants and nutrients entering water bodies. Thanks to technological and management advancements, substantially fewer people now die from extreme events, despite an increase in such events [Douris et al. (2021)]. Catchment model simulations fed with observational data in real-time have the potential to further reduce negative impacts on societies and ecosystems.

In some cases, engineered infrastructure can go beyond restoration and enhance natural water functions. For example, managed aquifer recharge, artificial glaciers, and rainwater harvesting can enhance water storage and availability for both people and nature. There is thus immense potential to restore the damaged infrastructure functions of the global water cycle and to develop new ones in smart ways that bring multiple benefits for human well-being and ecosystem services.

Figure 1: Freshwater Outside a Planetary Safe Operating Space with Respect to Both Green (a) and Blue (b) Water



Notes: Green water typically refers to plant-available water in soil and transpired by plants, while blue water refers to water in rivers, lakes, and groundwater. The transgressions of other planetary boundaries (c) are linked to the freshwater crises, as freshwater interacts with ecosystems, climate, and land processes and plays an important role in the transport of nutrients and pollutants.

Source: Panels (a) and (b) are taken from Porkka et al. (2024) and (c) is from Richardson et al. (2023).

2.2 The Anatomy of the Global Water Cycle

To understand the infrastructure functions of the global water cycle, one needs to first grasp its overall structure. In the simplest terms, the water cycle can be described by stocks and flows (Figure 2). Major freshwater stocks include atmospheric moisture, soil moisture, surface water, groundwater, and frozen stocks. The water cycle, including oceans, is closed at the planetary scale in the sense that only a negligible amount of water escapes from or is formed on Earth. Nevertheless, the total amount of water flows and stocks on land depends critically on the many local cycles of water across the world, without which the total flows would be substantially diminished. Hence, one can think of the global water cycle as an aggregate of many nested water cycles.

The atmospheric moisture stock is the smallest stock but regulates the largest flows. On average, the atmosphere holds only 13,000 cubic kilometers of water but transports over 500,000 cubic kilometers

per year of evaporation to precipitation flows over both ocean and land [Oki and Kanae (2006)]. The atmospheric moisture storage capacity (or moisture holding capacity) depends on air temperature. The warmer the air, the more moisture it can hold. Hence, global warming overall increases moisture content in the air, thereby supercharging the global water cycle.

The soil moisture stock is also small, yet it supports all land-dwelling life. The stock size of 17,000 cubic kilometers is similarly considerably small in comparison to the flows it serves: Around 74,000 cubic kilometers per year is evaporated from land, and 120,000 cubic kilometers per year is precipitated over land [Oki and Kanae (2006)]. Soil moisture storage capacity depends on soil texture and rooting depth, of which, in particular, root depths can change over time depending on hydroclimate and ecosystem adaptation. For example, forests tend to root deeper than grasslands and croplands, and a more variable hydroclimate tends to favour forest ecosystems to

develop deeper roots. However, there are limits to adaptation. If drought conditions surpass critical thresholds or if the rate of hydroclimatic change exceeds the rate of ecosystem adaptation, forests face the risk of collapse into a degraded, low-canopy state.

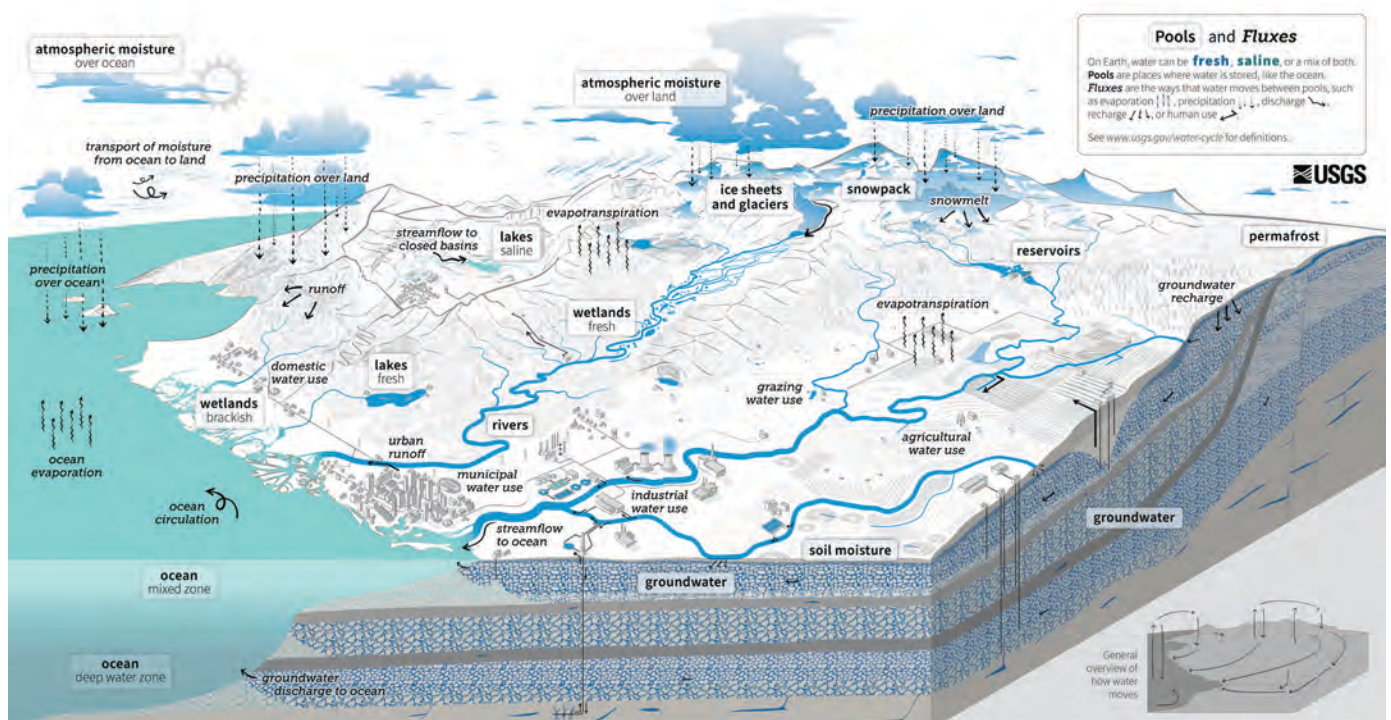
Surface water stocks include water in lakes, wetlands, and rivers; constitute major habitats for life in their own right; and are the components most recognized, used, and modified as engineered infrastructure in human societies. Lakes contain most water (180,000 cubic kilometers, of which half is saline and half is fresh), followed by wetlands (17,000 cubic kilometers) and rivers (2,200 cubic kilometers) [Collins et al. (2024); Oki and Kanae (2006)]. The throughflow of rivers globally is around 37,000 cubic kilometers per year (Collins, et al., 2024). Engineered structures cumulatively have a water storage capacity of 7,420 cubic kilometers and an artificial terrestrial surface water area of 304,600 square kilometers [Lehner et al. (2024)].

Groundwater and frozen water stocks are arguably the largest stocks with the longest turnover times. While some of these stocks are continuously

replenished and well connected to the water cycle, large parts are fossil in nature and do not replenish after withdrawal or irreversible melting. Due to their sheer size and relatively unpolluted states, both stocks play a critical role in supplying stable water sources for both ecosystems and human societies [Immerzeel et al. (2019)]. As managed infrastructure, surface water can be pumped into the ground, an approach used in water treatment and for storing water to even out water distribution (substantially more cost-effective and intrusive than the construction of reservoirs), where the geology allows. Artificial glaciers have been used for thousands of years in mountain regions to support water use throughout the year. Anthropogenic climate change is now the leading cause of diminishing glacier size and their ability to act as water towers.

The capacity of landscapes to retain water is critical for water availability and variability. Both natural green and blue water storage have been declining overall due to human activities such as deforestation and groundwater depletion, while engineered structures for blue water storage have overtaken some of the storage capacities from natural

Figure 2: The Global Water Cycle



Source: US Geological Survey (2022).

systems (Box A, Table A1). Ecological water storage is cost-efficient, driven by the sun's energy through photosynthesis, and has the capacity to repair damage and adapt to shocks. Biodiverse ecosystems in harmony with local social and environmental conditions are considerably more resilient and adaptable than plantations and monocultures. Increasing green water stocks has a multiplier

effect, amplifying water cycling and enhancing blue water availability by increasing downwind rainfall, infiltration, and recharge. Nevertheless, where local blue water availability is critically scarce, care needs to be taken to ensure that increases in green water storage capacities do not come at the expense of local blue water availability.

Box A: Keeping Water in the Landscape as a Resilience Strategy

The capacity to retain and slow water flows through landscapes is essential for water availability and variability over land. To understand this, one can conduct a thought experiment: Imagine Earth's land surfaces were covered in asphalt, with no capacity to retain water. In this scenario, precipitation events would lead to spikes in flooding, with water flowing directly to the ocean rather than being available on land. Evaporation from land would likely be more than halved, resulting in substantially reduced precipitation. However, the conclusion is not simply to maximize water storage and turn all land into marshes, but to strategically reinvigorate and combine different types of storage that can be maintained in the prevailing local hydroclimatic conditions.

Different water stocks and storage capacities have different functions (Table A1). For example, larger root-zone storage capacities, combined with high infiltration rates, help terrestrial ecosystems bridge dry spells at the weekly and monthly time scales, while groundwater and glaciers can sustain croplands and societal water use at the sub-annual and annual time scales. Increases in storage capacity may not always increase desirable functions and may have repercussions for other downstream and downwind water stocks. For example, increases in atmospheric moisture storage capacity caused by global warming intensify both droughts and extreme precipitation, which increases the need for the capacity to dampen variability in land systems, such as through larger interception and soil moisture storage. Larger increases in such storage capacity can, however, by capturing the precipitation and returning the moisture to the atmosphere, reduce water availability in downstream streams while increasing precipitation in downwind areas.

Storages and storage capacities in natural systems can likely be increased substantially through restoration. The total amount of natural water stored on land has declined overall, largely due to human water consumption and anthropogenic global warming, indicating a large potential for restoration, even if not all losses can be easily reversed. Among others, soil moisture declined by 2.6 trillion tons between 2000 and 2016, equivalent to a cube container 1.5 times taller than Mount Everest [Seo et al. (2025)]; around 21 percent of wetlands by area have been lost between 1700 and 2000 [Fluet-Chouinard et al. (2023)]; natural lakes have lost 728 gigatonnes of water over the period 1992 to 2020 [Yao et al. (2023)]; and glaciers worldwide have lost 6,300 gigatonnes in mass from 2000 to 2023 [Zheng et al. (2025)]. Reservoir storage capacities have increased, but with diminishing returns in the amount of water that can be stored per unit of capacity constructed, due to increasing sedimentation and evaporation [Li et al. (2023)].

Keeping water stocks and flows in the landscape for resilience requires a threefold approach: (1) providing water variability buffers in landscapes for societies and ecosystems, (2) limiting droughts and precipitation extremes, and (3) building societal capacities to absorb shocks, adapt, and transform. A variety of natural storage capacities can be enhanced, including restoring rivers, wetlands, and landscapes, while ensuring that the interventions align with local societal, ecological, and climatic contexts. The interplay and trade-offs between storage capacities need to be accounted for to prevent undesirable downstream/downwind impacts. At the same time, additional benefits can be gained by accounting for the ability of healthy and biodiverse ecosystems to adapt to changing hydroclimate.

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Box A *continued***Table A1: Overview of Storage Capacities**

Storage Types (Storage Size, and Average Residence Time)	Role for Water Availability and Variability	Recent Status	Actionability Potential
Atmospheric Moisture (~13,000 km ³ , nine days)	Higher storage capacity increases global precipitation overall but also leads to more extremes.	Increasing due to global warming. The atmospheric moisture-holding capacity increases by seven percent per 1°C of warming.	Can be effectively reduced by limiting global warming.
Soil Moisture (~17,000 km ³ , 1-2 months)	Higher capacity increases plant water availability over time, and reduces flood risks and erosion.	Overall increasing. Increasing where ecosystems are adapting to droughts, and decreases caused by deforestation, land degradation, ecosystem transitions, and locally less variable climate.	Some decreases can be avoided by preventing forest loss and land degradation. Increases can be encouraged by ecosystem restoration, by promoting the diversity of hydraulic traits, and agricultural practices such as rainwater harvesting and maintenance of high infiltration rates.
Surface Water			
Lakes (~180,000 km ³ , 50-100 years)	Higher capacity allows for attenuation of precipitation, sedimentation, water purification, and larger aquatic ecosystems, as well as stable supply of water for societal use.	Decreased due to water use and diversions, agricultural expansions, construction of engineered structures, and increased evaporation rates.	Can be increased by lake, wetlands, and river restorations. Cost and difficulty to restore vary greatly.
Wetlands (~17,000 km ³)			
Rivers (~2,200 km ³ , 2-6 months)			
Engineered (~7,420 km ³)	Provides electricity, water for societal use, and flood control.	Overall increase. Decreases caused by sediment accumulation and global warming, and increases due to new dam constructions.	Can be increased by new constructions. Old dams can be decommissioned to restore natural river flows.
Glaciers (20-100 years)	Provides melt water for ecosystems and societal use.	Geological storage capacity can be permanently reduced by landslides and other materials replacing the melted glaciers. The actual storage capacity is also temperature-dependent.	Can be substantially increased by limiting global warming and black carbon emissions. Reductions can, to some extent, locally be slowed down by the use of reflective blankets, for example. Artificial glaciers are other local measures to increase actual storage capacity.

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Box A *continued*

Groundwater (100-10,000 years)	Providing stable sources of water for both terrestrial and aquatic groundwater-dependent ecosystems and societies.	Decreasing irreversibly due to subsidence [Herrera-García et al. (2021)].	Reductions can be effectively reduced by preventing overexploitation.
Plant Surface and Litter Interception (<1 day)	Storage capacity contributes to local and fast moisture recycling and prevents floods. May, however, also reduce river flows and groundwater recharge.	Increasing due to increases in biomass, and decreases due to tropical forest loss.	Unknown.

Source: Lehner et al. (2024); Falkenmark et al. (2019); Oki and Kanae (2006).

2.3 The Infrastructure Functions of the Global Water Cycle

The water cycle is a unique feature of Earth and what makes life as we know it possible. While water is ubiquitous in the universe and across the solar system, Earth is the only known planet where freshwater remains in circulation with negligible amounts escaping into space. The patterns and dynamics of freshwater's continuous circulation are not only a result of Earth's atmosphere, plate tectonics, topography, and the sun's radiation, but also critically shaped by living ecosystems that store soil moisture, uphold evaporation, and sustain downwind rainfall. In other words, the world we see today—including the evolution of humanity itself—is very much the result of a co-evolutionary dance in which water shaped life and life shaped water over the 3.5 billion years of biosphere history.

The becoming of modern humans itself was shaped by water: from the migration of early hominins out of Africa mediated by prevailing hydroclimatic conditions, and the early river valley civilizations that controlled water through dams, canals, and levees, to the contemporary globalized world, whose daily operations for food, energy, and transport shape and are shaped by the global water cycle. Given this historical context, bearing in mind that the human enterprise as a whole emerged from the interplay with the water cycle, it is no surprise that the water

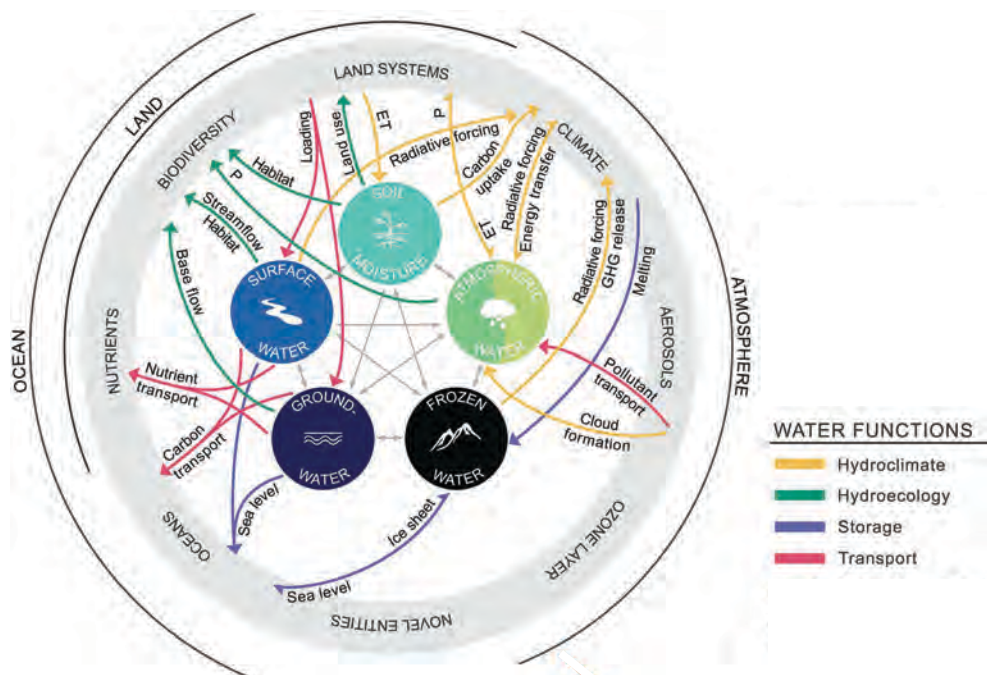
cycle provides a number of major functions that are critical for the conditions on which all economic activities and growth depend.

At the Earth system scale, the remarkably stable Holocene climate, which began roughly 11,700 years ago, provided the predictability required by modern, agriculture-based civilization. There is no evidence to support that complex and sedentary human civilizations can be sustained at a large scale outside these conditions. These stable Holocene-like conditions on Earth rely on four major functions served by the freshwater cycle: storage, transport, hydro-ecological regulation, and hydro-climatic regulation, see Figure 3 [Gleeson et al. (2020)].

Water storages are an important feature of the water cycle that is critical for regulating sea levels, sustaining base flows to rivers, and buffering fluctuations in water availability (see Section 2). If all the ice on Earth melted, the sea level would rise about 70 meters.

Water transport distributes water, as well as sediments, nutrients, and carbon, thereby shaping landscapes, nutrient cycles, and carbon cycles. Transport on Earth is predominantly by suspension or dissolution in water, and only secondarily through non-water transport mechanisms such as atmospheric dust and animal movements.

Figure 3: The Five Major Freshwater Stores in the Earth System and Four Types of Functions



Notes: Abbreviations: Hydroclimatic and hydroecological regulation are shortened to hydroclimate and hydroecology; P refers to precipitation; and ET refers to total evaporation from land, also known as evapotranspiration [Gleeson et al. (2020)].

Source: Gleeson et al. (2020).

Together, these freshwater dynamics regulate hydroecology by enabling photosynthesis and by supporting and providing habitats for all terrestrial and aquatic life on and near land. First, water is a key ingredient in photosynthesis, which powers all life on Earth, by converting solar energy into chemical energy while producing oxygen. Around half of global photosynthesis takes place on land, and the other half in the oceans. Second, water regulates aquatic life, with quantity, flow rates, and the waxing and waning of water determining the conditions of freshwater habitats such as rivers, lakes, wetlands, and coastal systems.

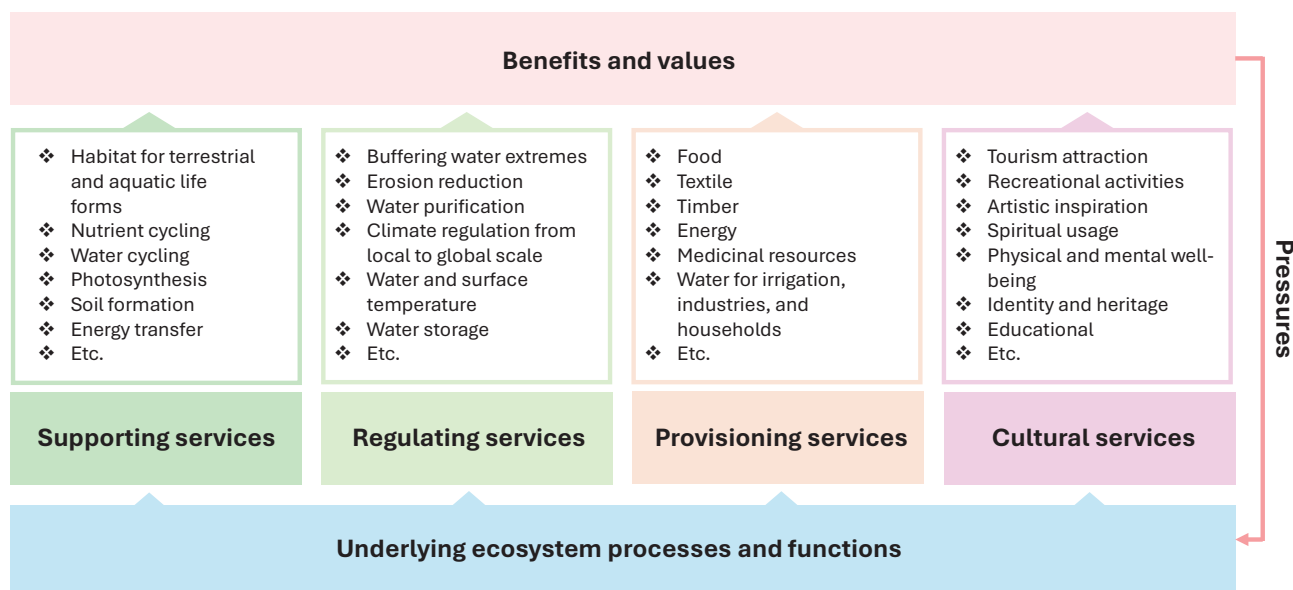
Finally, freshwater directly regulates Earth's hydroclimatic conditions by affecting how much of the sun's energy is bounced back into space, surface temperatures, and precipitation patterns. Indirectly, water also regulates Earth's climate by controlling land carbon sinks and, thereby, greenhouse gas concentrations in the atmosphere. Water in the form of clouds, snow, and ice determines how much of the sun's energy is bounced back to space and how much of Earth's outgoing radiation leaves for space. Evaporation and soil moisture provide cooling and, as such, regulate surface temperature and precipitation patterns.

For example, a lack of soil moisture leads to higher temperatures, which explains how droughts can drive fires; irrigation can cool the land surface, thereby decreasing the land-ocean gradient and delaying the onset of the Indian monsoon; and high humidity can lead to deadly wet heatwaves beyond human physiological tolerance [Russo et al. (2017)]. Moreover, water availability regulates photosynthesis for carbon sequestration, as well as the release and retention of powerful greenhouse gases, such as nitrous oxide and methane, in aquatic ecosystems. All the freshwater-dependent carbon stocks—land ecosystems, coastal ecosystems, and lakes and reservoirs—store together more than 350 times the current annual human emissions from fossil fuel use [Friedlingstein et al. (2025)].

2.4 Ecosystem Services Provided by Freshwater

There are four categories of ecosystem services that are all relevant to water (Figure 4): the supporting services, such as nutrient cycles and oxygen production, which underpins all other services; provisioning services, such as the production of water, energy, and food; regulating services, such

Figure 4: Ecosystem Helping Linking Water Cycle Processes with Human Well-Being



Notes: Ecosystem services originate from underlying ecosystem processes and water functions (see Section 2.3) and deliver benefits that can be valued in non-monetary and monetary terms. Based on the ecosystem cascade model [Haines-Young and Potschin (2010)].

Source: Haines-Young and Potschin (2010).

as the control of climate and disease; and cultural services, such as recreation, tourism, and spiritual gratification. Ecosystem services originate from the structure, processes, and functions of the water cycle, and deliver goods and benefits that can be estimated in non-monetary and monetary terms. The framework is designed to facilitate categorization with respect to human use rather than a mechanistic description of the water cycle and nature; hence, there are inevitably overlaps between the different types of services and between functions and services. The supporting services of the water cycle include water cycling, nutrient cycling, and habitat provision, and largely overlap with what we term “functions” (Section 2.3).

Provisioning water services for ecosystems includes the stable supply of clean water for agriculture, industry, and households, as well as all food, biofuel, textile, energy, genetic material, and medicinal resources, and other goods production reliant on the use of water.

Globally, agriculture is by far the largest user of the provisioning water service. Globally, about 70 percent of water withdrawn is used by the agricultural sector, followed by industries and domestic water use at roughly 15 percent each. Around 80 percent of irrigation water comes from

renewable sources, and 20 percent from groundwater depletion. For example, the severe 2022 drought in California and Arizona led to an 80 percent increase in vegetable producer price in the United States from November 2021 to November 2022, and the 2022/23 droughts in Southern Europe led to a 50 percent price increase across the European Union in 2023 [Kotz et al. (2025)].

Regulating water services of ecosystems includes flood and erosion control, water purification, and hydroclimatic regulation. First, ecosystems provide flood and erosion control by attenuating extreme precipitation and acting as physical barriers. Forests and woodlands substantially reduce surface flows by increasing rainfall infiltration to soil and root zones. Wetlands likewise reduce peak flows by quickly storing large amounts of water and releasing it slowly over the course of days and weeks. In coastal regions, coastal ecosystems such as mangrove forests, salt marshes, and coral reefs act as natural barriers against storm surges and tidal waves. Second, ecosystems provide water purification analogous to the steps in a water treatment plant, through physical filtration, chemical absorption/adsorption, and biodegradation. For example, wetlands and riparian ecosystems slow flows, allowing for particles to settle; microorganisms such as bacteria, fungi, and algae break down organic

waste through decomposition; and in coastal systems, mussels, oysters, and clams actively filter water from pollutants. Third, the regulation of hydroclimate by ecosystems, such as precipitation, temperature, and carbon sequestration, vastly exceeds that of engineered systems. Clearly, such regulatory services are critical for planetary and human health.

Cultural water services of ecosystems include aesthetic values, recreation and tourism, spiritual significance, and cultural heritage. The aesthetic values include, for example, the beauty of water as a source of artistic inspiration in paintings, music, poetry, and literature more broadly. The recreational values include enabling water-based activities and sports (such as fishing, swimming, and kayaking), as well as attractions for tourism. Spiritual values include rituals and ceremonies related to water, such as sacred places and pilgrimage sites, which are ill-captured by monetary valuations. The role of water in cultural heritage includes, for example, how the identities of coastal and maritime communities are tightly interwoven with water alongside architectural and cultural history, as in the city of Venice.

2.5 Navigating Surprises, Tipping Points, and Unintended Consequences

The natural infrastructure of the global freshwater cycle is a living system. Unlike engineered infrastructures, there is no central control room, no on-off buttons. Instead, the living water infrastructure systems have the resilience capacities to self-regulate, recover, adapt, and evolve. These capacities are what make the services from ecosystems so life-essential, cost-effective, and multi-beneficial. However, seemingly slow changes can lead to abrupt collapses that are difficult to reverse, and with open system boundaries, unanticipated consequences across distances are not uncommon. Therefore, ensuring the long-term sustainability of natural infrastructure critically hinges on management that can navigate complexity, account for uncertainties, and maintain resilience—the capacity to retain core functions in the face of change and perturbations [Folke (2006); Folke (2003); Li et al. (2018)].

First, ecosystems and water cycle processes can fail abruptly and persistently, along with the functions and services that they provide. Such collapse and regime shifts can happen when the system loses its resilience, i.e., the capacity to absorb shocks, to adapt, and transform [Falkenmark et al. (2019); Gordon et al. (2008)], and are of great concern to managers because they are not easy to anticipate, and failures are difficult to reverse. For example, runoff in around one-third of the watersheds in southeastern Australia did not return to predrought levels even seven years after the Millennium drought, suggesting a regime shift to a different hydrological state [Peterson et al. (2021)]. The reasons for the shift are still under investigation, with one hypothesis being that ecosystem adaptation to the drought conditions has elevated transpiration rates.

The capacity to anticipate such a shift remains limited, suggesting a continued need for flexible and adaptive governance [Moore et al. (2024)]. Moreover, collapses and regime shifts can occur long after pressures start to accumulate, far exceeding typical policy-making time frames. For example, past decades of greenhouse gas emissions are projected to have locked in glacier retreats, affecting water resources for billions of people [Immerzeel et al. (2019)], and the potential die-back of large parts of the Amazon rainforest will affect precipitation in downwind regions [Flores et al. (2024)].

Second, ecosystem service managers are confronted with pressure-impact relationships across well-established system and administrative boundaries. Water does not recognize boundaries: Blue water flows connect stakeholders between upstream and downstream, rural and urban, as well as within or between basins; atmospheric moisture flows connect evaporation with precipitation up to thousands of kilometers away [van der Ent et al. (2010)]; and international trade links water use and scarcity in one region to countries on completely other continents [Allan (1997); Hoesktra and Hung; Zeitoun et al. (2010)].

Climate change further increases the risk of concurrent water hazards, either by increasing the likelihood of drought synchronization through phenomena such as the Rossby wave and the El Niño Southern Oscillation (ENSO) [Anderson et al. (2019); Cai et al. (2021); Jeong et al. (2025)], or through a statistical increase of the chances of

co-occurrence caused by higher drought frequency [Mehrabi and Ramankutty (2019)]. Combined with physical and virtual water connectivity, compounded events are more likely to threaten water, food, and energy security across countries and continents.

Third, changes to the water cycle and societies' responses dynamically interact, forming a co-evolving system that allows new patterns to unfold. As a result, well-intentioned solutions can backfire, leading to unpleasant surprises. Time and time again, flooding catastrophes occur despite massive investments in levees, and agricultural systems collapse despite investments in irrigation systems [Baldassarre et al. (2015)]. However, because humans have agency, such unfolding patterns are by no means deterministic, which makes them particularly poignant to recognize. A common pattern is when solutions backfire by creating a false sense of abundance or safety and masking risks. A tragic and clear example of this is the continuous increase in flood protection around the city of New Orleans in the United States, which has led to extreme, low-probability flooding and allowed continued city development, as it gave a sense of safety [Kates et al. (2006)].

However, Hurricane Katrina in 2005 was too severe for the levees, resulting in devastating damage. In addition, accelerating growth can bring overshoot. For example, water demand initially satisfied can drive further growth in water use, leading to an overshoot of water resources before effective countermeasures can be taken. Rapid irrigation roll-out in India, for example, caused groundwater tables to drop unsustainably.

Moreover, the tragedy of the commons can occur when a shared common-pool resource is exploited competitively rather than collaboratively, leading to its ultimate collapse, as in the drying of the Aral Sea in Central Asia [Micklin (1988)]. Maladaptive lock-in can occur when solutions once adopted are hard to reverse or adjust, even as conditions have changed. For example, barriers in waterways globally, more than one million just in Europe, prevent free-flowing rivers and harm aquatic ecosystems, but remain costly and difficult to remove, even as their downsides outweigh the benefits [Belletti et al. (2020)]. Some lock-ins occur due to the high cost of reversal in financial or reputational terms, others due to cultural or institutional inertia.

Moving forward, sustainable and resilient infrastructure interventions need to consider balancing multiple ecosystem services as well as interconnectivity and dynamics. These interventions include mediating both physical and immaterial systems, such as norms, knowledge, and institutions. For example, to deliver sustainable and resilient outcomes, 'soft' investments in diversified farm and off-farm livelihood strategies and nutrition programs can be necessary.

For example, Chapter 7 underscores the importance of local institutional capacities for the protection of Ramsar wetlands. Moreover, holistic considerations across sectors, scales, and distances are necessary. Similarly, solar-powered hydro pumps also pose risks and trade-offs, including groundwater depletion, and require proper governance and incentives (Chapter 7). Another example is ecological restoration, which has been shown to positively impact hydropower generation (Chapter 8).

Governance needs to build resilience accounting for human-nature interactions, for example, by adopting established resilience principles: maintaining diversity and redundancy, managing connectivity, managing slow variables and feedbacks, fostering complex adaptive systems thinking, encouraging learning, broadening participation, and promoting polycentric governance systems (see Chapter 11), [Biggs et al. (2012)].

2.6 Concluding Remarks

The global freshwater system is a prerequisite for societies to thrive. Comprised of many nested water cycles, the global water stocks and flows are living infrastructures in a continuous co-evolutionary dance between the climate, ecosystems, and societies. Megacities are often clustered around coasts and rivers, just as species- and carbon-rich ecosystems cluster in regions with stable, plentiful water. At the same time, ecosystems drive water cycling across landscapes by retaining water in their root zones, providing moisture for rainfall, and replenishing aquifers with the help of the sun's energy.

In the Anthropocene, freshwater—the bloodstream of the biosphere and the lifeblood of civilizations—is now changing rapidly, and sometimes abruptly

and persistently. The stability of the planetary infrastructure can no longer be taken for granted. The functions and services of the global water cycle can respond to pressures abruptly and persistently.

Systems boundaries are open, and failures in service deliveries can be interconnected and cascade through space and time via international trade and atmospheric teleconnections. At the same time, societies interact and co-evolve with ecosystems in ways that are difficult to anticipate and understand.

Moving forward, infrastructure interventions need to smartly retain water flows in the landscapes to resiliently manage water availability and

variability. Investing in natural solutions is cost-effective, as ecosystems have an inherent capacity to respond to shocks and adapt to change. Biodiversity increases response diversity, providing more resilience than planted monocultures. Green water resources have been overlooked in the past, but are particularly important for sustaining the water cycle, including facilitating aquifer recharge and generating downwind rainfall. The potential to restore both green and blue water stocks is substantial. Investments in integrated governance and natural water infrastructure systems, while accounting for interactive human-nature dynamics across space and time, are critical for resilient and sustainable outcomes.

Box B: Shrinking Glaciers and Water Insecurities in the Himalayan Region—Implications for Infrastructure and Investment

The Hindu Kush Himalayan (HKH) region spans over 3,500 kilometers from western Afghanistan to eastern Myanmar and is often referred to as 'Asia's water tower' with the largest ice reserves outside the polar regions. Ten major Asian rivers (Table B1) support millions of people through some of the world's largest irrigation networks and hydropower energy sources [Sharma et al. (2019)]. Warming at around 0.42°C per decade (1980-2018) has accelerated glacier melting, mass loss, as well as the destabilization of glacial lakes [Yao et al. (2022)].

Water availability in the Himalayan catchments is strongly influenced by the balance between glacier mass and catchment dynamics of changing rainfall to runoff. Snow and glacial melt begin in the summer season, whereas winter brings snowfall at higher elevations replenishing glacier mass. Glaciers in general are retreating and losing mass across the globe [Zemp et al. (2017)]. Over a short period, glacier melt may increase under a warming climate. Glacier runoff is expected to reach its maximum or "peak water" at some point in time due to accelerated melting occurring under a warming climate; beyond this point, runoff will steadily decline as glacier storage diminishes [Huss and Hock (2018)].

Water security in HKH is under increasing pressure from accelerating glacier melt, shifting snow cover dynamics, and growing monsoon variability (Kulkarni et al., 2021). Glacier retreat is reducing long-term natural water storage, while increasingly erratic monsoon rainfall intensifies both flood risk and seasonal water stress.

Coupled with rising water demand, these changes undermine the reliability of water supplies for irrigation, ecosystems, and energy production. The resulting instability poses serious risks for the 240 million people living in the HKH and the nearly 1.9 billion inhabitants dependent on the 10 major river basins originating in the region [Khanal et al. (2021); Romshoo et al. (2022); Vaidya (2015)].

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Box B *continued***Table B1: Ten Big River Systems of the HKH Region with Key Characteristics of the Basins**

River basins	Countries shared	Population (million)	Area (km ²)	Glacier area (km ²)	Glacier number	Ice reserve (km ³)	Average annual discharge (m ³ /sec)
Amu Darya	Afghanistan, Tajikistan, Turkmenistan, Uzbekistan	27.19	645,870	2,566	3,227	163	1,376
Brahmaputra (Yarlung Tsangpo)	China, India, Bhutan, Bangladesh	64.63	528,083	14,020	11,497	1,303	21,261
Ganges	India, Nepal, China, Bangladesh	539.43	1,001,090	9,012	7,963	794	12,037
Indus	Pakistan, India, China, Afghanistan	244.31	1,116,350	21,193	18,495	2,696	5,533
Irrawady (Ayeyarwady)	Myanmar, China	40.18	426,393	35	133	1	8,024
Mekong (Lancang)	China, Myanmar, Lao PDR, Thailand, Cambodia, Viet Nam	74.58	841,337	235	482	11	9,001
Salwee (Nu/Thanlwin)	China, Myanmar, Thailand	18.19	363,898	1,352	2,113	88	1,494
Tarim	China	10.65	929,254	2,310	1,091	379	1,262
Yangtze (Chang Jiang)	China	600.92	2,066,050	1,660	1,661	121	28,811
Yellow River (Huang He)	China	192.86	1,073,440	137	189	9	1,438

Sources: Glacier area, number and ice reserve: Bajracharya et al. (2014); Population and basin areas: Sharma et al. (2019); Discharge: Eriksson et al. (2009).

Changes in glacier dynamics, river runoff, water availability, and timing

Glaciers across the region have experienced sustained and likely accelerating mass loss over the past two decades [Bolch et al. (2012); Käab et al. (2012)]. Estimated glacier mass loss averaged -19.0 ± 2.5 Gt per year between 2000 and 2018 [Shean et al. (2020); Yao et al. (2022)]. Projections indicate that glacier loss will continue to accelerate throughout the 21st century under all climate scenarios. Even under an optimistic pathway consistent with limiting global warming to 1.5°C, as envisioned in the Paris Agreement, about one-third of Himalayan glacier mass will be lost by the end of the century. Under business-as-usual scenarios, losses could reach nearly two-thirds of total glacier ice [Kraaijenbrink et al. (2017)].

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Box B *continued*

Glacier and seasonal snow melt are crucial for buffering dry season flows, especially in the western HKH and Indus basin, where cryospheric contributions to streamflow are proportionally higher than in the monsoon-dominated eastern basins such as the Ganges and Brahmaputra. Meltwater runoff is therefore vital for sustaining downstream agriculture and hydropower [Azam et al. (2021)]. For example, in the Indus basin approximately 60 percent of total irrigation water withdrawals during the spring originate from mountain snow and glacier melt, contributing an estimated 11 percent to overall crop production. Across the Indus and Ganges basins, around 129 million farmers depend directly on snow and glacier melt for their livelihoods [Biemans et al. (2019)].

Looking ahead, Khanal et al. (2021) assessed future water availability across 15 rivers in high mountain Asia and found that while total annual water availability in headwater regions may increase, significant changes are expected in the timing and seasonal distribution of flows [Lutz et al. (2014)]. Recent projections suggest that in the Upper Indus basin, the onset of glacier and snow melt could shift earlier by one to two months, intensifying risks for meltwater-dependent sectors and underscoring the need for targeted adaptation measures [Lutz et al. (2022)].

Impacts of disasters on infrastructure and investments

Glacier systems across the HKH are increasingly destabilized by climate change, manifested in accelerated glacier retreat and the expansion of glacial lakes [Shugar et al. (2020)]. Many of these lakes are unstable and can trigger glacial lake outburst floods (GLOFs), generating sudden, debris-filled floods that pose threats to downstream infrastructure. Climate change is increasing the frequency and intensity of GLOFs, glacier collapses, extreme rainfall, and compound hazards in glacier-fed basins, substantially increasing risks to roads, hydropower facilities, and human settlements [Bhardwaj et al. (2025); Gao et al. (2024)].

In recent years, the HKH region has experienced a series of distinctive disasters, including single, multi-hazard and cascading impacts. Major glacier-related hazards between 2013 and 2025 have caused extensive damage to infrastructure and livelihood systems. Reported losses amount to hundreds of millions of dollars, reflecting both direct physical damage and wider indirect economic impacts.

Compounding hazards have emerged as a growing concern in recent decades. Single or multi-hazard events—such as glacier collapses, rock- and ice-avalanches, and GLOFs—can interact with extreme rainfall and steep terrain to produce cascading disaster sequences.

These compound events often exceed the design thresholds of structural defenses and overwhelm early warning mechanisms, resulting in damaging impacts that propagate far beyond the initial trigger location. Such disasters have caused extensive damage to critical infrastructure and socio-economic systems. Notable examples include the 2013 Uttarakhand floods in India (losses exceeding USD2 billion); the 2021 Chamoli disaster which resulted in USD223 million in direct losses to two hydropower projects; the 2021 Melamchi disaster in Nepal causing USD497 million in economic losses; the 2023 Sikkim disaster with damages reaching approximately USD2.4 billion.

Adaptation to water resource variability in the HKH increasingly depends on diverse water storage solutions—both traditional and modern, and at multiple scales—to manage erratic precipitation and glacier melt. Options such as artificial glaciers, ice stupas, small reservoirs, tanks, and ponds are widely employed to buffer seasonal water shortages and support irrigation and domestic supply. In high-altitude regions like Ladakh, artificial glaciers [Nüsser et al. (2018)] and reservoirs are complemented by community-managed ponds and the maintenance of traditional canals, boosting resilience to diminishing snow and rainfall [Hock et al. (2019)]. However, large reservoir projects in high altitude areas remain vulnerable to complex geomorphological processes that can destabilize landscapes [Li et al. (2022)]. As emphasized by the International Water Management Institute (2022), water storage strategies should be prioritized according to geographical, socio-economic, and cultural contexts. Effective storage encompasses both surface options (e.g., reservoirs, lakes, glaciers, snowpack, and ponds) and subsurface options (e.g., soil moisture and groundwater), particularly in the context of climate change and related hydrological crises.

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Box B *continued*

Escalating risks underscore the importance of robust early warning systems that integrate remote sensing with hydrometeorological, glaciological, and geomorphic monitoring. Advanced forecasting and real-time data networks are critical for delivering timely alerts to downstream communities and infrastructure, underpinning climate-resilient infrastructure essential for sustainable development in unstable mountain regions [Wang et al. (2022)].

HKH countries have prioritized a combination of large-scale and small-scale storage solutions to modulate seasonal water availability as a climate adaptation strategy. Pakistan, India, Nepal, and Afghanistan, for example, need targeted investments in reservoirs, managed aquifer recharge, and small-scale systems, such as delay-action dams, to store monsoon runoff for dry season use, and offset shifting melt runoff patterns. Notable projects include:

Budhi Gandaki Multipurpose Project (Nepal): designed for hydropower generation (1,200 MW), flood control, and dry season flow regulation with an estimated construction cost of USD2.6 billion.

Baghdara Dam (Afghanistan): proposed on the Kabul River to provide large-scale seasonal storage and hydropower with an estimated cost of about USD562 million.

In the long term, better protection for infrastructure in high-risk areas, particularly near rivers (e.g., hydropower facilities), will require investment in river embankments, slope stabilization, early warning systems, and climate-resilient construction. Such measures are essential to reduce flood and landslide risks while enhancing resilience to climate-induced water variability across the HKH region.

Policy recommendations and investment priorities

Mainstream multi-hazard risk assessment across all stages of development planning and infrastructure design by systematically evaluating existing and emerging hazards during project formulation, implementation, and operation. Risk reduction should be embedded in site selection, design standards, construction practices, and operational protocols. In glacial and riverine areas, early warning systems must be strengthened through integrated satellite and ground-based monitoring, complemented by community radios, sirens, and mobile alerts to ensure timely dissemination. Cross border data sharing among Himalayan countries is essential to support upstream–downstream and transboundary hazard communication.

Land use and watershed policies should encompass the dynamic nature of mountain landscapes, enforcing no-build zones on floodplains, river terraces, and unstable slopes, and restricting deforestation and mining in vulnerable watersheds. Science-informed policies that recognize interconnected climatic, ecological, and social pressures are critical for safeguarding water security, protecting investments, and enhancing regional stability through coordinated transboundary action.

Priority investments should focus on climate-resilient infrastructure, institutional capacity building, and governance reforms, alongside the systematic adoption of nature-based solutions to reduce disaster risks. Water storage options—from local ponds to medium and large dams—should be carefully assessed based on water demand, environmental sustainability, seismic risk, fragile geology, topography, and projected climate change impacts. In high-altitude regions, targeted investments in glacier risk monitoring, combined with robust early warning systems integrating both ground-based observations and remote sensing, are essential to anticipate cascading hazards.

Financing and governance strategies should leverage blended finance and risk-mitigation measures to support large-scale infrastructure beyond public budgets, enabling the climate-proofing of hydropower, transport, and dam safety. Strong public–private partnerships that incorporate risk-sharing instruments, performance-based returns, and transparent governance can mobilize private capital while delivering sustainable climate adaptation outcomes.





CHAPTER 3

THE INDIAN SUBCONTINENT AND THE WATER CYCLE FROM MONSOON TO OCEAN

HIGHLIGHTS

- The Indian subcontinent illustrates how water operates as a tightly connected source-to-sea system. With only around 4 percent of the world's water supporting 18 percent of the world's population, water security depends on the stability of monsoon-driven flows linking Himalayan headwaters, intensively cultivated river basins, aquifers, deltas and a densely populated 7,500 km coastline.
- Water quantity and quality move together across basins. In systems such as the Ganga–Brahmaputra–Meghna and the Krishna, floods, droughts, sediment transport, groundwater depletion and pollution jointly influence agricultural productivity, infrastructure performance, urban water reliability, and coastal ecosystem resilience, requiring basin-scale rather than project-level responses.
- Natural ecosystems function as economic infrastructure. From the Western Ghats to the floodplains of Assam and coastal deltas, floodplains, wetlands, tanks, mangroves and aquifers store water, regulate flows, sustain fisheries, and reduce fiscal exposure. Increasing the capacity of nature to hold water and harvest the monsoon strengthens economic resilience.
- Climate change amplifies land–river–ocean feedback. The Indian Ocean—already the world's hottest—is warming rapidly and experiencing significant climate-driven changes, influencing monsoon variability, precipitation intensity, and sea-level rise, which in turn increases salination risks in coastal aquifers. Ocean acidification and stratification — partly influenced by altered runoff patterns — affect marine productivity, reinforcing the interconnected nature of inland and coastal water systems.

This chapter illustrates, through the example of the Indian subcontinent, the hydrological framework presented in the previous chapter. Using real river basins, landscapes, and institutions, it shows how monsoon rainfall, soils and forests, rivers and aquifers, deltas, and the Indian Ocean operate as a single interconnected system. Water in this region is embedded in agriculture, industries, energy, urban growth, and livelihoods; changes in runoff, sediment flows, and ocean conditions therefore propagate across economic and social systems. The chapter highlights why retaining water in landscapes and aligning infrastructure with basin-scale hydrology are central to long-term resilience.

3.1 Water as Living Infrastructure: The Subcontinent Mosaic

The subcontinent's water systems illustrate how freshwater operates as living infrastructure. Green water (soil moisture and ecosystems) and blue water (rivers and aquifers) interact through a highly seasonal monsoon, shaping agricultural production, industrial manufacturing, urban development, energy generation, and coastal ecosystems across the subcontinent. The stability of this hydrological system underpins economic growth, while its variability exposes infrastructure, livelihoods, and fiscal systems to significant risk.

Although South Asia's aggregate water endowment is substantial, it is unevenly distributed across both space and time. India alone provides home to nearly one-fifth of the world's population who depends on roughly four percent of global renewable freshwater resources. Much of this water is delivered within a short monsoon window, creating pronounced seasonal variability and huge challenges in storage and allocation. Spatial and temporal mismatches between water supply and demand, along with variable rainfall, generate recurring cycles of flood and drought. At the same time, economic expansion and urbanization are increasing water demand across agriculture, industry, and domestic sectors [Piesse (2020)].

These pressures are further compounded by climate variability and long-term climate change, which alter precipitation patterns and hydrological regimes [IPCC (2022)]. Such shifts intensify stress on rivers, aquifers, and ecosystems. The Indian Ocean, which is already the world's warmest ocean, is experiencing

rapid warming and increased variability, reinforcing uncertainty in monsoon behavior and downstream water risk [IPCC (2022)].

These interconnected pressures reveal the systemic nature of water risk across the subcontinent. In this context, water management cannot be treated as a single-sector issue. Decisions about storage, irrigation, groundwater extraction, land use, and coastal protection influence supply reliability, infrastructure performance, and economic resilience. Managing water as living infrastructure therefore requires aligning built systems with ecological processes across the entire source-to-sea continuum.

Across the Indian subcontinent, high climate variability and large population dependent on agriculture shape patterns of water availability and use. Roughly 70 percent of the population remains rural, with agriculture as the primary livelihood. The agriculture sector employs between 33 percent of the labor force in Sri Lanka to 70 percent in Afghanistan, and contributes between 12.8 percent of GDP in Sri Lanka and around 33 percent in Nepal. These figures underscore the centrality of water to economic and social stability across the region.

Agro-ecological conditions vary sharply. Approximately 20 percent of the subcontinent consists of hills and mountains with steep slopes; 19 percent is humid or moist sub-humid lowland; 29 percent is dry sub-humid; and 32 percent is semi-arid and arid lowland [FAO and World Bank (2001)]. Within India alone, 15 agro-climatic regions and 20 agro-ecological regions have been delineated to guide land-use planning, grouped into six ecosystems and further divided into 60 sub-regions [Indian Council of Agricultural Research (2008)].

These agro-ecological differences shape cropping systems, irrigation intensity and water demand. Rice-based systems dominate humid and sub-humid zones, while semi-arid and arid regions face high evapotranspiration and greater irrigation dependence. The spatial mismatch between rainfall patterns and agricultural demand generates persistent structural imbalances in water availability across river basins, reinforcing the need for basin-scale planning that aligns infrastructure investment with hydrological realities.

India's water system is governed by the monsoon, one of the most powerful seasonal climate systems in the world. Rainfall is highly variable across both space and time, with most precipitation concentrated in the southwest monsoon months. Annual rainfall norms (1971-2020) range from 486 mm in western Rajasthan to 3751 mm in Meghalaya in northeastern India [India Meteorological Department (2024)], creating profound contrasts in water availability across river basins.

This variability is increasing. Two-thirds of India's 4,500 *tehsils* (administrative regions) have experienced a rise in heavy rainfall days over the past decade, with precipitation increasingly occurring in short, intense bursts [Prabhu and Chitale (2024)]. These shifts amplify flood and landslide risks, particularly in urban areas where drainage systems and land-use planning have not kept pace with rapid expansion.

Beyond seasonal variability, land-atmosphere interactions play a critical role in shaping rainfall patterns. In regions such as the Western Ghats, forest cover, soils, and agricultural landscapes influence moisture recycling and local precipitation dynamics, linking land management directly to water availability downstream. Changes in land cover — whether through deforestation, irrigation expansion, or soil degradation — can therefore alter runoff, storage, and drought intensity. These land-rainfall linkages are expanded in the following chapter.

In this context, the monsoon is not only a climatic driver but part of a coupled land-water-atmosphere system. Managing forests, agricultural systems, and urban landscapes therefore influences not just water storage and runoff but also the stability of rainfall patterns on which the subcontinent depends.

3.2 Rivers, Basins, and the Geography of Water Mismatch

Water across the Indian subcontinent is best understood at the river basin scale. Major systems such as the Indus, Ganga-Brahmaputra-Meghna (GBM), and the large peninsular rivers connect highly diverse climatic zones, linking glacier-fed headwaters, monsoon plains, and densely populated deltas across national boundaries.

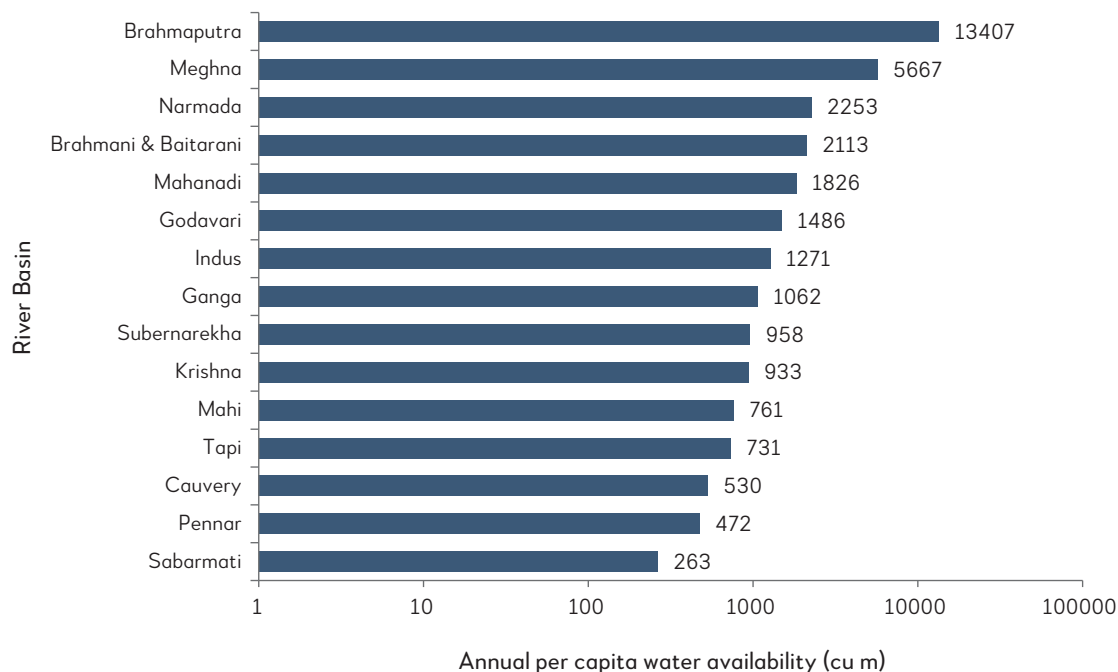
Although South Asia's aggregate water endowment is substantial, it is unevenly distributed across both space and time. Within the Indus basin alone, precipitation ranges from more than 1,000 mm in humid sub-tropical zones to less than 100 mm in arid desert regions [Laghari et al. (2012)]. Similar contrasts characterize other basins, reflecting sharp differences in rainfall, soils, storage capacity, and institutional management.

Per capita renewable freshwater availability varies widely across the region, from around 89 m³ in the Maldives to nearly 39,700 m³ in Bhutan. India's per capita availability is approximately 1,500 m³, compared with about 8,000 m³ in Nepal, below the global average of roughly 20,000 m³ per capita per year [FAO (2025)]. These figures highlight structural scarcity in several countries, though actual access depends on infrastructure, storage, financial resources, and governance capacity.

In India, average annual precipitation from rain and snow amounts to roughly 4,000 billion cubic meters (BCM). Of this, an estimated 1,869 BCM appears as natural runoff, but only about 1,123 BCM is considered utilizable due to topography, storage constraints, and uneven distribution [Central Water Commission (2010)]. Around 40 percent of utilizable surface water is concentrated in the GBM basin, while western and peninsular basins possess far less.

This spatial concentration creates a persistent mismatch between water supply and demand. Northern and northeastern basins benefit from perennial, glacier-fed systems but face recurrent flooding, particularly in stretches of the Ganga-Brahmaputra floodplains in Assam and Bihar [IPCC (2022)]. In contrast, many western and peninsular rivers are monsoon-dependent and seasonal and have much less utilizable water. For instance, while the per capita water availability is above 2000 m³ per annum in perennial river basins of Brahmaputra, Meghna, Narmada, and Brahmani & Baitarani, it is below 1000 m³ in seasonal river basins of Sabarmati, Pennar, Cauvery, Tapi, Mahi, and Krishna [Bassi et al. (2024)].

Yet, the western and peninsular rivers support irrigated agriculture and expanding urban centers, increasing vulnerability to drought. Urban expansion further compounds risks, as insufficient drainage infrastructure contributes to flooding even during moderate rainfall events.

Figure 5: Variations in Annual per Capita Water Availability by River Basin in India

Source: Bassi et al. (2020).

Understanding these basin-level imbalances is central to infrastructure planning and climate resilience. Storage, inter-basin transfers, groundwater management, and coastal protection decisions all influence how upstream variability translates into downstream risk. Basin-scale planning therefore becomes essential not only for allocation, but for managing the cascading effects of floods, droughts, and sediment dynamics across the entire source-to-sea system.

3.3 Small Water Bodies, Distributed Storage, and Underground Water

Across the Indian subcontinent, small water bodies like tanks, ponds, wetlands, and village reservoirs have long functioned as distributed storage systems, capturing monsoon rainfall and holding water in the landscape to support agriculture, groundwater recharge, and local livelihoods. In states such as Tamil Nadu, cascading tank systems [Gopalakrishnan (2014)], historically moderated seasonal variability, reduced flood peaks, and provided dry-season irrigation, illustrating how local storage complemented river-basin systems.

Though the total number of wetlands in India grew by 9 percent and the total area increased by 4 percent between 2006-07 and 2017-18, it is the man-made wetlands (such as reservoirs, tanks, and aquaculture ponds) that have increased by 11 percent in number and expanded by 13 percent in area [Bassi et al. (2025)]. This reflects a shift toward using wetlands for water storage and commercial aquaculture rather than only ecological conservation.

Rapid urbanization and rising water demand, however, have degraded or eliminated many of these systems. In cities such as Delhi and Bengaluru, more than half of traditional water bodies have disappeared [Gandhiok (2024)], reducing local storage capacity and increasing both flood and drought vulnerability.

Revitalizing these distributed systems can complement large-scale infrastructure. By enhancing local storage and recharge and buffering rainfall variability, small water bodies reduce pressure on major river basins and improve groundwater stability. As climate extremes intensify, integrating such blue-green infrastructure into basin-scale planning becomes an important component of long-term resilience.

Groundwater functions as an invisible lifeline across the Indian subcontinent, buffering seasonal variability and sustaining domestic supply, irrigation, and industry. In many regions, aquifers provide the stability that surface water systems cannot offer, particularly during delayed monsoons or extended dry periods. As climate variability intensifies, this buffering role becomes increasingly important for food production and economic resilience.

Further, surface water and groundwater interact in a river basin. Several studies demonstrate that such interactions are an integral part of the hydrological cycle, characterized by continuous and dynamic exchange, leading to water gains and losses [Arya et al. (2025)].

For instance, under a scenario of controlled groundwater pumping during non-monsoon and recharge during monsoon in Ramganga sub-basin in India, groundwater recharge and river contribution to groundwater could increase by 14 percent and 31 percent, respectively over a 10-year period [Surinaidu et al. (2016)]. But, baseflow will decrease, hence adversely impacting the river flows.

Beneath parts of northwestern India, satellite and geophysical studies have identified palaeo-channels (buried remnants of ancient river courses now filled with sediment) associated with former river systems, including those linked to the historically referenced Saraswati River [Indian Space Research Organisation (2019); Central Ground Water Board (2017)]. While these features are not active underground rivers in the conventional sense, they illustrate the complex hydrological history of the subcontinent and highlight how past river systems continue to influence present-day groundwater storage patterns.

At the same time, groundwater abstraction has expanded rapidly. India is among the world's largest users of groundwater, and declining water tables are particularly evident in parts of northwestern India, including the Punjab and Haryana, where irrigation-intensive agriculture has placed sustained pressure on aquifers [Central Ground Water Board (2017)]. Energy-linked pumping incentives and rising demand from growing urban and industrial centers have further contributed to extraction pressures (this is discussed in the irrigation chapter of the report).

Efforts to strengthen groundwater governance have expanded in recent years. Programs such as the Atal Bhujal Yojana have supported improved monitoring, community participation, and incentives for more sustainable groundwater use [Khanduja et al. (2023)]. While implementation outcomes vary across districts, these initiatives reflect growing recognition that aquifer sustainability is central to long-term water security.

Groundwater dynamics are not isolated from river basins and coastal systems. Over-extraction can reduce baseflows to rivers, alter surface water availability, and increase vulnerability to drought, while quality concerns, including salinity and contamination, pose additional risks in both inland and coastal aquifers. Managing groundwater as part of the broader source-to-sea system is therefore essential to reducing cascading water risks.

3.4 Large Infrastructure and Changing Water Systems

Large-scale water infrastructure (dams, reservoirs, canals, and diversions) has played a central role in supporting agricultural expansion, urban supply, and energy generation across the subcontinent. India has created approximately 300 billion cubic meters of reservoir storage capacity, reshaping the seasonal distribution of monsoon flows. However, storage is unevenly distributed across basins. In river systems such as the Tapi, Krishna, and Narmada, storage capacity exceeds 50 percent of average annual flows, while in the Ganga and Brahmaputra–Barak basins it remains below 20 percent [Central Water Commission (2010)]. These contrasts influence flood control, irrigation reliability, and downstream sediment dynamics.

Irrigation potential refers to the area that could be irrigated given available water resources and infrastructure. Nationally, total irrigation potential has been assessed at around 140 million hectares, divided between surface water (76 million hectares) and groundwater (64 million hectares). Of this, about 56.5 million hectares of surface irrigation potential and 62.2 million hectares of groundwater potential have been created, while actual utilization remains lower at approximately 42.8 million hectares for surface water and 48.4 million hectares

for groundwater [Central Water Commission (2010)]. The gap between potential created and potential utilized reflects distribution inefficiencies, maintenance challenges, energy supply limitations, and uneven access across regions. This report's chapter covering irrigation explores these basin-wide trade-offs further.

In heavily regulated basins such as the Krishna, large storage has improved irrigation reliability but also altered natural flow regimes and sediment transport. Reservoir regulation modifies flood peaks and seasonal discharge, while sediment trapping behind dams reduces sediment delivery downstream [Central Water Commission (2010); Vörösmarty et al. (2003)]. Infrastructure has therefore both enabled development and reshaped hydrological and ecological processes. Understanding these trade-offs is essential for aligning future infrastructure investment with basin-scale resilience and source-to-sea stability.

3.5 From Project Thinking to Basin Thinking

Water governance in India is constitutionally devolved to the states, while interstate rivers may be regulated at the national level under parliamentary legislation [Inter-State River Water Disputes Act, (1956)]. In practice, however, most major rivers cross state boundaries, yet planning and allocation decisions are often taken within administrative rather than hydrological boundaries. This institutional fragmentation contributes to recurring disputes, inefficiencies, and delayed responses to basin-wide stress.

Moving from project-level interventions to basin-scale management is therefore essential. In river systems such as the Ganga basin, which covers multiple states and international borders, water stress, pollution, and flood risk cannot be addressed through isolated infrastructure investments alone. Basin planning requires reliable hydrological data, transparent allocation mechanisms, and coordination across irrigation, urban supply, industry, and environmental flows.

There is significant scope for improving efficiency within existing systems. Conservative estimates suggest that up to 20 percent of currently used

irrigation water could be saved by 2050 through wider adoption of micro-irrigation technologies [Chaturvedi et al. (2020)]. In the industrial sector, water-use standards for thermal power plants have been tightened in recent years, while domestic initiatives under programs such as Mission LiFE promote behavioral change toward water conservation. However, scaling these measures depends on robust water accounting systems that track withdrawals, actual consumption, conveyance losses, and reuse across sectors [Bassi et al. (2020)].

Wastewater management represents another critical basin-scale challenge. As of 2021, treatment capacity covers only about 44 percent of urban sewage generation [Central Pollution Control Board (2021)]. Domestic wastewater annual generation is projected to increase substantially by 2050 [NITI Aayog (2018)].

Without expanded treatment and reuse, polluted return flows compromise downstream water quality and increase health and environmental risks. Strengthening the financial viability of wastewater treatment and reuse projects will be central to closing this gap [Bassi et al. (2024); Gupta et al. (2025)]. This includes performance-based incentives and improved cost recovery.

Shifting from project thinking to basin thinking therefore requires institutional reform, improved data systems, and financing models that align water allocation, efficiency, and environmental sustainability across the full source-to-sea continuum.

3.6 Ridge to Reef: Rivers, Deltas, and the Ocean Connection

India's deltas and coastal ecosystems illustrate how hydrological, ecological, and climatic processes converge at the end of the source-to-sea continuum. River discharge regulates salinity, nutrient supply, and sediment delivery to estuaries and near-shore waters, shaping coastal geomorphology and marine productivity. Where freshwater inflows decline or sediment is trapped upstream, coastal systems become more exposed to erosion, salinity intrusion, and sea-level rise [Syvitski et al. (2005); Central Water Commission (2010)].

In basins such as the Krishna, large-scale storage and diversion have improved irrigation reliability but altered downstream flow regimes and sediment delivery, contributing to deltaic vulnerability rise [Syvitski et al. (2005); Central Water Commission (2010)]. These dynamics highlight that infrastructure decisions taken inland reverberate across coastal systems.

Groundwater extraction in coastal aquifers further modifies this balance. Falling freshwater tables enable saline intrusion, particularly in low-lying delta regions, compounding risks from sea-level rise and storm surges [IPCC (2022)]. At the same time, mangroves and coastal wetlands function as natural infrastructure, attenuating storm energy and stabilizing shorelines, thereby buffering both marine and inland systems [IPCC (2022)].

Changes in the Indian Ocean are also reshaping inland water risks. Rapid ocean warming, increasing stratification, and acidification are altering cyclone intensity, coastal productivity, and the physical and chemical conditions of near-shore waters [IPCC (2022)]. Increased freshwater runoff from major river systems contributes to upper-ocean stratification, affecting nutrient mixing and marine ecosystems. Ocean-atmosphere interactions influence monsoon behavior and precipitation variability across the subcontinent, while sea-level rise and stronger storm surges increase saline intrusion into coastal aquifers and soils [IPCC (2022)]. River discharge and sediment plumes further influence coastal fisheries and near-shore ecosystem productivity. These interactions demonstrate that rivers, deltas, and the ocean form an integrated hydrological system in which upstream land-use, infrastructure, and governance decisions interact with ocean dynamics to determine long-term resilience.

3.7 Climate Stress and Cascading Risks

Climate change is intensifying pressures across the subcontinent's interconnected water systems. Rising temperatures, shifting monsoon dynamics, glacier retreat in the Himalayas, and more frequent compound flood-drought events are increasing variability across the hydrological cycle [IPCC

(2022)]. These shifts affect water availability, food production, energy systems, urban infrastructure, groundwater stability, and coastal resilience.

Himalayan-fed basins, altered snowmelt, and rainfall patterns are modifying seasonal flows, increasing short-term flood risk while heightening long-term uncertainty in dry-season supply. In peninsular India, more intense rainfall combined with rapid urbanization has amplified urban flood exposure, while prolonged dry spells continue to strain groundwater-dependent agriculture. Along the coasts, sea-level rise and stronger cyclones interact with upstream sediment dynamics and water diversion to increase deltaic vulnerability.

These risks are not independent. Floods mobilize pollutants and sediments; droughts concentrate contamination and intensify competition among users; groundwater depletion increases coastal salinity intrusion; ocean warming alters monsoon behavior. As climate variability accelerates, infrastructure designed around historical hydrological norms becomes progressively misaligned with emerging realities.

India's experience illustrates how cascading risks propagate across the full source-to-sea system. Addressing them requires moving beyond sectoral responses toward integrated planning that aligns basin governance, infrastructure investment, ecosystem protection, groundwater management, and coastal adaptation. The challenges examined in this chapter, including storage trade-offs, irrigation efficiency, sediment dynamics, wastewater treatment, and ocean feedbacks, are not separate issues but interconnected dimensions of water security under climate stress.

Understanding and managing these interactions will be central to sustaining economic growth, reducing fiscal exposure, and strengthening resilience in water-stressed regions across the Indian Ocean and beyond.

3.8 Policy Implications

The Indian sub-continent requires a 'new paradigm' to adapt to changing climate and monsoon variability and become water resilient. To achieve

this, managing water from source-to-sea is of paramount importance. Based on the analyses presented in this chapter, the following policy measures will be crucial:

- **Mainstream granular risk assessments, stress test existing water-related infrastructure, in order to identify gaps and invest early to climate-proof water infrastructure and services:** Such assessments can be undertaken at the hydrological or administrative scale. They are important to identify the water sources, such as rivers, wetlands, aquifers, etc., and water supply and sanitation services which are at high risk to climate extremes. The information generated can be used to prioritize investments to reduce climate induced risk on water systems. Such assessments should be widely shared between countries in this region, given the interconnectedness of water resources and shared risks, and also to mobilize finances toward a common cause.
- **Manage water demand through reducing losses and improving water use efficiency:** This can be achieved through plugging leakages in the conveyance systems and adoption of water efficient technologies, such as drip and sprinklers for irrigation. At present, only about 21 percent of 70 million hectares of irrigated land amenable for micro irrigation in India is covered by drip or sprinkler technologies. Non-revenue water losses are of the order of about 40 percent. This offers a huge scope to reduce losses and manage water demand, which will ensure better utilization of available surface water and groundwater resources. Given the existing surface water-groundwater interactions, the water conserved can be redirected to support essential environmental flows in rivers.
- **Invest in alternate water sources to reduce pressure on freshwater resources:** Investments to strengthen used water infrastructure and scaling up reuse of treated used water for non-potable uses are the most promising approaches to reduce demand on freshwater resources and improve the ambient water quality. This requires preparation of city specific reuse plans that include a water balance, identification of reuse avenues, financial models, and institutional structure to implement such projects. As per estimates, this will unlock an economic opportunity of USD 26–35 billion by 2047, encompassing both market potential and investment opportunities in India [Gupta et al. (2025)].
- **There are also emerging discussions around policy solutions that can be considered, for example, implementing strong governance measures for groundwater management:** Consider establishing tradable groundwater rights and entitlements, metering irrigation wells, and pricing energy, which are some of the most crucial interventions for managing groundwater over-exploitation, especially in coastal areas where salinity ingress is accelerated by groundwater abstraction. Input subsidies can be more targeted toward lower-income communities. Finally, policies providing incentives to farmers for growing crops suitable for the local agroecology will be a most important nudge for shifting behavior to using groundwater sustainably.



CHAPTER 4

FLYING RIVERS

THE INVISIBLE AND DEEP CONNECTIONS OF OUR SHARED WATER

HIGHLIGHTS

- Atmospheric “flying rivers” transport vast amounts of moisture across borders. This is critical to the distribution of rainfall across regions. Many countries derive more than 50 percent of their rainfall from moisture generated elsewhere.
- Atmospheric moisture flows are especially critical for inland regions to receive precipitation. Regions such as Central Asia and West Africa rely heavily on moisture from other countries.
- Analysis shows that forest and wetland landscapes are associated with a more intense propagation of moisture across boundaries. Grasslands and agricultural landscapes contribute to cross-border moisture flows, but the impact is weaker.
- Conserving water-rich ecosystems such as forests and wetlands is thus critical to sustaining the water cycle and regional water security and requires payment mechanisms to support such conservation to maintain nature as infrastructure.

4.1 Introduction

Countries share water resources through three main pathways: terrestrial water flows (such as rivers and subsurface flows), virtual water trade (water embedded in traded goods and services), and atmospheric moisture flows (flows of water vapor from sources of evapotranspiration to precipitation sinks). Atmospheric flows are the largest of the three, distributing around 120,000 cubic kilometers of water annually. Moisture feeds into rainfall, which is the fundamental source of land-based freshwater,

replenishing rivers and groundwater, infusing the soil with water, and ultimately becoming available for plants and ultimately returning to the atmosphere.

First coined to describe the aerial transfer of water vapor from the Amazon rainforest to other downwind regions, “flying rivers” today describes the vast system of atmospheric water flows [Nobre (2014); Silva et al. (2025)]. A key pathway involves plants taking up soil moisture (green water) and returning it to the atmosphere through evapotranspiration. Once formed, the water vapor moves into the

atmosphere and is distributed by winds and pressure systems until it condenses to precipitate onto land and sea, within short distances or thousands of kilometers away [van der Ent et al. (2010), Gimeno et al. (2012)]. Forests are known to play a key role in supporting this global hydrological cycle [Sterling et al. (2014); Ellison et al. (2017); Cui et al. (2022)].

Though vital, the stability of this process is often neglected in policy debates and in human water indicators [World Bank (2025)]. Understanding the global moisture cycle and how humans impact it is crucial for guiding land use, conservation, and infrastructure policy.

With climate change and land-use changes potentially destabilizing such flows, there is now greater urgency to view this hydrological cycle as a key global public good [Keys et al. (2016); te Wierik et al. (2020); GCEW (2023)].

These atmospheric connections mean that infrastructure reliability in one region can depend on ecosystem conditions in another, reinforcing the need to manage water systems at landscape and regional scales. Deforestation and land-use changes, in upwind regions, can reduce downwind precipitation [Devaraju et al. (2015); Smith et al. (2023); Araujo and Hector (2024)], streamflow [Wang Erlandsson et al. (2018)] and water availability [Weng et al. (2018)] and trigger feedback with drought [Schumacher et al. (2022)] and climate. Economic activities, particularly agriculture, can then be negatively affected by upwind deforestation [O'Connor et al. (2021), Chrysafi et al. (2022); Niasulu et al. (2024); Pranindita et al. (2025)]. Preserving and restoring nature as infrastructure is then essential for maintaining the availability (and stability) of water in downwind regions.

Leveraging existing datasets and the latest research, this chapter begins with a quantitative analysis that documents the extent of cross-border moisture flows followed by an analysis of how land-use patterns affect these flows. The chapter ends with a brief policy discussion.

4.2 A Global Moisture Input-Output Table

This chapter is based on several of the latest publicly available geospatial datasets on atmospheric moisture connections [De Petrillo et al. (2025a)] and land vegetation.¹

Global Moisture Data

The RECON dataset developed by De Petrillo et al. (2025a) offers reliable cell-scale atmospheric moisture connections data with global coverage and on the annual scale. This dataset is based on atmospheric moisture tracking output from the UTrack model [Tuinenburg et al. (2020)], which maps the global connections between water sources (evaporation) and sinks (precipitation). Specifically, the RECON dataset ensures matching bilateral exchange between a source and a sink at the annual scale. It allows the convenient computation of precipitation-shed and evaporation-shed for any location in the world.² This research aggregates cell-scale data to the country, then presents country-specific bilateral moisture flows.

A Global Moisture Input-Output Table

A precipitation shed refers to the upwind sources of evaporation that lead to rainfall in a specific downwind location. Precipitation shed accounting simply means tracing back the total rainfall (in cubic meters) at any location to all possible sources of moisture. With this method, a global bilateral moisture flow among economies is constructed, resulting in a global input-output table for water. A few trends become clear:

- Annually, countries around the world receive a total volume of 120,000 cubic kilometers of rainfall. This is roughly 30 times the total amount of freshwater withdrawn by humans per year.³ Rainfall refills almost one-third of the total surface freshwater stock, which is the

¹ European Space Agency Landcover dataset: [ESA/CCI viewer](#).

² A precipitation shed is the entire upwind region (land and ocean) that supplies the water vapor for a specific location's rainfall. An evaporation shed describes the downwind area that receives precipitation originating from the evaporation of water in a single, specific upwind location. One defines the source of a location's rain, while the other defines where a source's evaporated water ends up as rain. Both concepts help understand how water evaporates from one place, travels through the air, and falls as rain in another, often distant, location.

³ [Water Use and Stress - Our World in Data](#): Annual human withdrawal of freshwater was around 3.99 trillion cubic meters in 2014.

most direct essential source of water for human activities. This total rainfall on land is generated by moisture from both land and ocean, and land itself contributes about 45 percent [De Petrillo et al. (2025b)] despite accounting for 30 percent of Earth's total area.

- Aside from the ocean, Brazil is the largest source of moisture for rainfall on land globally, mainly due to its massive rainforest. Its total moisture generation amounts to 7,900 cubic kilometers per year, more than the annual discharge volume of the entire Amazon River.⁴ Top foreign recipients of Brazil's moisture are largely neighboring countries (Peru, Bolivia, Colombia), but also include destinations 12,000 kilometers away, such as New Zealand.
- Other large moisture contributors are also countries with large land areas or high forest coverage. Following Brazil, Russia contributes 4,400 cubic kilometers, or 8.5 percent, to global land rainfall. China and the United States generate almost the same amount of moisture, and both account for six percent of the global total rainfall. The 10 main contributors account for more than half of global land moisture (Table 1).

Water interdependence between economies is not just linked to cross-border surface water bodies such as rivers and lakes. Cross-border rainfall via global moisture flow also presents another layer of freshwater interdependence. For countries where rainfall moisture is dominated by foreign sources, cross-border water governance then involves more than just transnational water bodies; it also includes activities that could affect upwind moisture generation, such as deforestation.

However, this perspective is largely neglected in the current water governance discussion. Traditional water governance frameworks focused solely on surface and groundwater flows may significantly underestimate transboundary water interdependencies.

To gain a deeper understanding, the bilateral moisture data are further aggregated to compute domestic, foreign, and ocean contributions for each economy. The analysis reveals that on average, countries received 71 percent of moisture from the ocean, 23 percent from another territory, and only 5.5 percent from domestic sources.⁵ No country has complete moisture self-sufficiency. Twenty-four countries are highly dependent on

Table 1: Top 10 Countries by Total Moisture Contribution

Countries	Precipitation to Other Economies (Billions of Cubic Meters)	Share of Total Land Precipitation (Percent)
Brazil	7,914	15.2
Russia	4,427	8.5
China	3,363	6.5
United States	3,216	6.2
Democratic Republic of the Congo	2,663	5.1
Canada	2,213	4.2
India	1,582	3.0
Australia	1,288	2.5
Peru	1,101	2.1
Colombia	1,053	2.0

Source: AIB staff estimates based on data from De Petrillo et al. (2025a).

⁴ Amazon River's discharge rate is 209,000 cubic meters/second, therefore multiplying it with the number of seconds in a year yields 6,600 cubic kilometers of annual discharge.

⁵ For each economy, the share of rainfall it receives globally is computed, and divided each by ocean, domestic land and foreign land contributions to precipitation. These shares are the average of each category.

moisture from abroad, with foreign upwind moisture contributing to more than half of their total rainfall. About 40 percent of economies receive more than 25 percent of their precipitation from foreign land sources.

Countries such as Equatorial Guinea (73 percent) and Uruguay (71 percent) demonstrate extreme vulnerability to changes in upwind moisture generation, while landlocked nations in Central Asia (Mongolia, Kyrgyzstan, Tajikistan) and Africa (the Central African Republic, Gabon, Cameroon) show a disproportionate reliance on transboundary atmospheric flows.

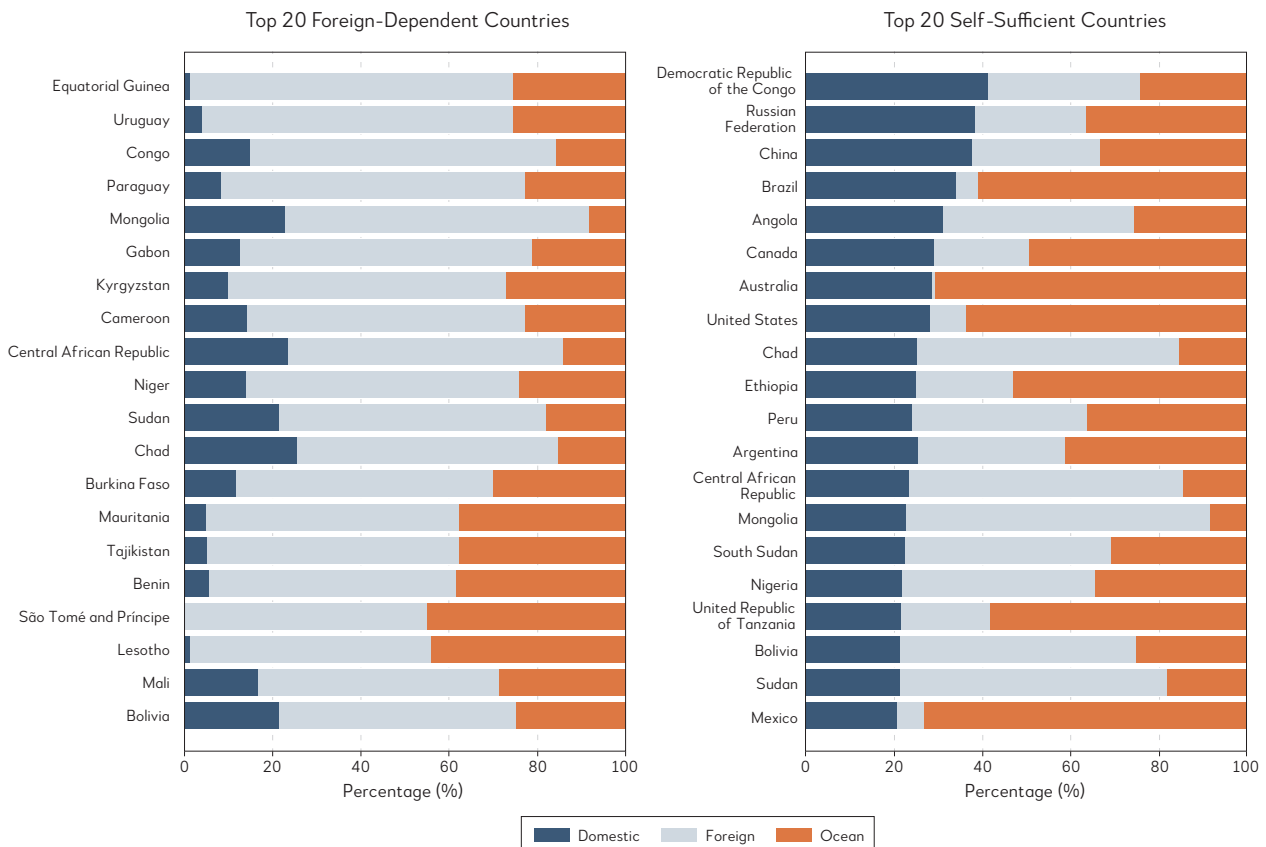
Landlocked countries generally face a disproportionately high level of foreign moisture dependence compared to global averages, with Central and West Asian landlocked nations deriving 51 percent of precipitation from foreign land sources (versus 23 percent globally) and African landlocked countries receiving 48 percent from foreign contributors.

Among these landlocked economies, Mongolia exhibits the highest foreign dependence at 69 percent, followed by Gabon (66 percent), Kyrgyzstan and Cameroon (63 percent), the Central African Republic (62 percent), and Niger (62 percent), indicating that water security for these nations is closely tied to upwind land-use decisions beyond their borders.

Russia is the dominant external moisture supplier to Central/West Asia (285 cubic kilometers per year reaching all 12 analyzed countries), while Ethiopia serves this role for Africa (397 cubic kilometers per year), establishing these nations as atmospheric water “superpowers” whose land-use policies have measurable downwind impacts across multiple landlocked neighbors.

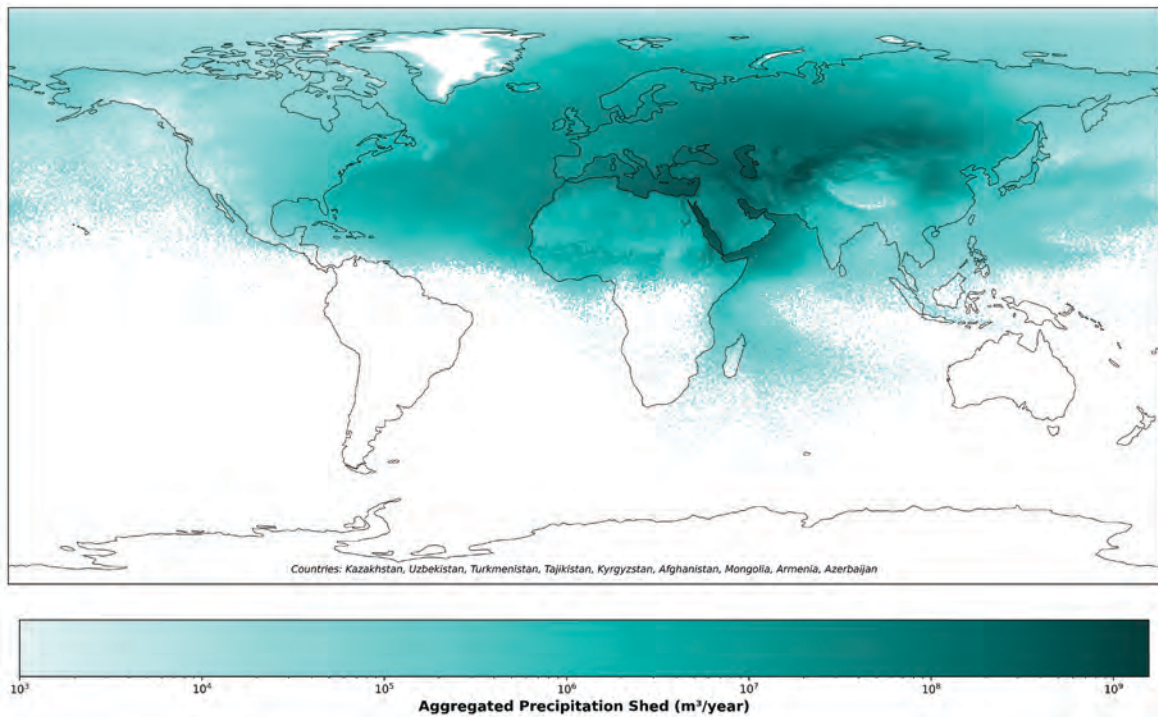
These findings underscore the need for atmospheric-hydrological cooperation and land-use policies that account for downwind moisture dependencies in regional development and climate adaptation strategies.

Figure 6: Interdependence of Land Moisture Between Economies



Source: AIIB staff estimates based on data from De Petrillo et al. (2025a).

Figure 7: Precipitation-Shed of Landlocked Central & West Asia (Aggregated by 9 Countries)



Source: AIIB staff estimates based on data from De Petrillo et al. (2025a).

4.3 Forests and Wetlands as Inland Moisture Pumps

Land surface vegetation is fundamental to the global moisture cycle, not just through transpiration that generates vapor in the air but also through the water-holding capacity of its massive ground root system. In particular, the relationship between the forest ecosystem and the moisture cycle is well studied, and further insights emerge from the analysis of the global network of reconciled atmospheric moisture connections [De Petrillo et al. (2025a)].

This section highlights the regression results between moisture volume and land vegetation coverage, which provide a direct, quantified understanding of the role of vegetation coverage in moisture cycles.

When controlling for total land area, forest and wetland shares emerge as land-use determinants of transboundary atmospheric moisture flows. Other vegetation types also support such flows, but their effects are smaller. Analysis of land cover proportions across 168 economies reveals that forest share is positively linked to moisture exports

to foreign countries and total moisture generation to the global system. A simple regression is carried out to examine the relationship between each country's moisture generation intensity and the shares of different land covers. Moisture generation intensity is defined as the amount of moisture generated per square kilometer of land. Control variables include the average distance to all other economies and the mean yearly temperature.

The results in Table 2 show that, on average, a one percentage-point increase in forested area correlates with an annual rise of 5,389 cubic meters per square kilometer in moisture generation intensity. Of this total increase, 1,256 cubic meters per square kilometer goes to domestic territories, while 4,134 cubic meters per square kilometer is transported to foreign territories. Wetlands also have high moisture generation intensity, though the overall land area is significantly smaller than that of forests. Compare to forest, agricultural land generates some moisture, but the intensity is weaker. Grassland generates significantly less moisture, while urban cover reduces moisture generation.

Table 2: Regression Between Moisture Intensity and Landcover

Independent Variables	Moisture Generation Intensity m ³ /km ²		
	To Domestic	To Foreign	Total
Agricultural Share (%)	6.232 (292.391)	3,339.413*** (845.801)	3,345.645*** (872.304)
Forest Share (%)	1,255.631*** (406.515)	4,133.806*** (697.628)	5,389.437*** (767.361)
Grassland Share (%)	671.173 (446.222)	1,342.408 (819.706)	2,013.581** (965.990)
Wetland Share (%)	-2,185.034 (1,628.572)	9,336.220*** (3,281.788)	7,151.185* (4,103.050)
Settlement Share (%)	-4,553.877** (1,860.349)	1,531.895 (1,660.359)	-3,021.981 (2,365.242)
Average Distance to All Other Regions (km)	9.685 (7.029)	-23.600*** (8.700)	-13.915 (11.919)
Mean Annual Temperature (Celsius)	2,101.794** (853.157)	11,589.670*** (1,588.617)	13,691.464*** (1,877.513)
Constant	-84,403.135* (48,348.268)	46,079.592 (78,111.420)	-38,323.532 (99,857.607)
Observations	168	168	168
R-squared	0.175	0.366	0.384
SE Type	Robust	Robust	Robust

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Source: AIB staff estimates.

Brazil, the Democratic Republic of the Congo, and Indonesia—countries with the largest areas of rainforest—are the leading global exporters of terrestrial moisture. The export volume denotes the quantity of moisture crossing national boundaries over land, excluding amounts retained domestically or discharged into the ocean. Collectively, these three economies export approximately 4,132 cubic kilometers of moisture annually to other territories, a figure comparable to global human freshwater usage per year. While their combined land area constitutes only about eight percent of the world's total terrestrial surface, they account for nearly one-quarter of global moisture exports.

It is not simply the size of forests that matter for global evapotranspiration. Forest connectivity is also directly and positively linked to local climate-regulating functions contributing to the stability of evapotranspiration and moisture recycling flows, which may be altered by

anthropogenic disturbances such as degradation and fragmentation, transforming a well-forested area into a weaker and less resilient source of moisture [Numata et al. (2021); Nguyen et al. (2025)].

Ecosystem Payment Mechanism for Cross-Border Moisture

Global moisture flow is asymmetric. Of the 13,180 cubic kilometers exchanged between countries per year, approximately 7,592 cubic kilometers (60 percent) is transferred from lower- to higher-income countries, whereas 5,587 cubic kilometers (40 percent) moves in the opposite direction. In short, low- and lower-middle-income countries are significant net “exporters” of moisture (1,544 cubic kilometers and 249 cubic kilometers net, respectively), whereas upper-middle-income countries are net importers.

This net positive transfer primarily results from tropical evapotranspiration in ecosystems of the developing economies and the higher concentration of natural resources and intact ecosystems. The primary contributors to inter-income-group moisture flows are tropical countries characterized by extensive forested areas.

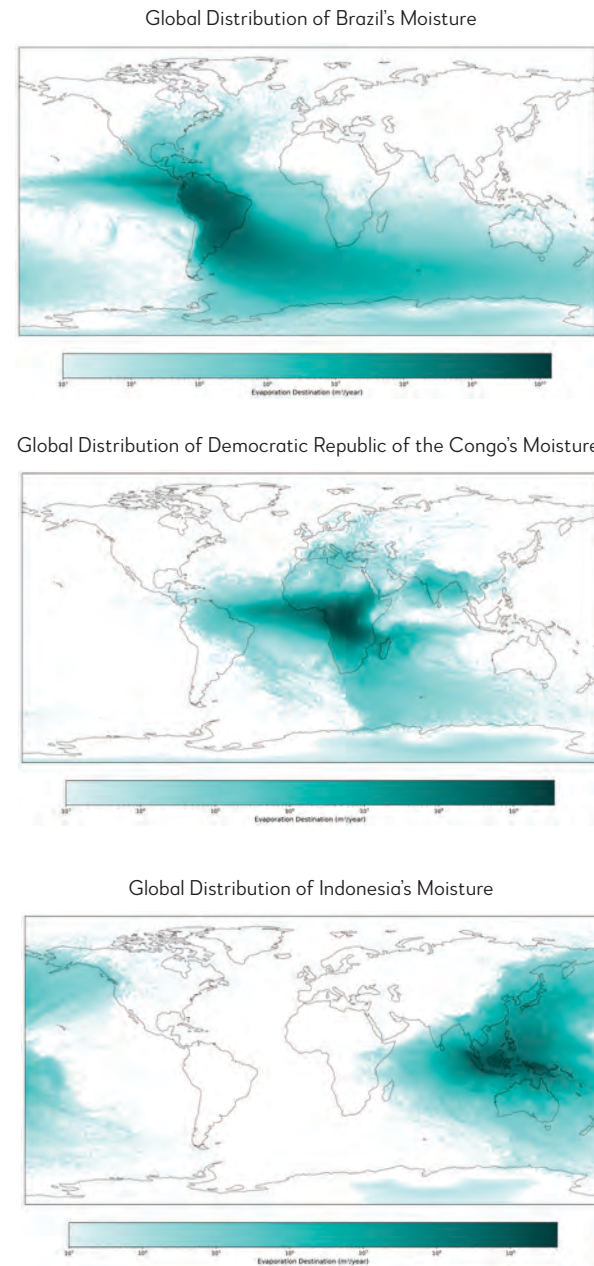
The Democratic Republic of the Congo (851 cubic kilometers per year), India (832 cubic kilometers per year), and Brazil (816 cubic kilometers per year) are the leading sources of these transfers, followed by Bolivia, Zambia, and Myanmar, among others, where intact ecosystems and agricultural landscapes produce considerable evapotranspiration. Thirteen out of the top 20 countries facilitating these flows are low- or low-middle-income countries.

If valued at a global average water tariff of USD2.76 per cubic meter, this unpriced “moisture subsidy” by lower-income countries would amount to an estimated USD5.53 trillion per year, which is 67 percent of the total GDP of all low and lower-middle-income countries (USD8.3 trillion).

Hence, establishing an ecosystem payment mechanism could mobilize public and private finance across moisture-importing and moisture-exporting economies to support the conservation of moisture-generating ecosystems. This mechanism could take the form of financing the conservation or restoration of upwind moisture-generating ecological systems, particularly forests, through a combination of public and private financial instruments that recognize nature as critical infrastructure. A recent joint report by AIIB, EBRD, and the Paulson Institute (2025) offers an overview of relevant and available public and private financing tools for financing nature as infrastructure.

Such a system would acknowledge the ecological interdependence identified through atmospheric moisture and offer climate-vulnerable moisture-exporting countries predictable funding for nature-based solutions, acknowledging the roles of governments, investors, and companies in shaping land-use incentives while supporting more predictable financing for climate-vulnerable regions.

Figure 8: Brazil, Democratic Republic of the Congo, and Indonesia Evaporation Shed



Source: AIIB staff estimates based on data from De Pettillo et al. (2025a).



CHAPTER 5

STRENGTHENING WATER INFRASTRUCTURE FOR RESILIENT AGRICULTURE INSIGHTS ACROSS ASIA⁶

HIGHLIGHTS

- Irrigation systems serve as foundational water infrastructures, critical for climate resilience, dry-season food production, and the well-being of rural households. Their performance is closely tied to watershed conditions, hydrological reliability, and climate variability.
- Irrigation rehabilitation generally boosts farm profitability, but its impact varies significantly across agroecological zones. In West Java, dry-season land expansion and yield improvements led to the doubling of production. However, in challenging environments such as semi-arid Nusa Tenggara and coastal South Sumatra, gains were modest and limited only to the rainy season. This underscores the limits of an irrigation-only solution.
- Tailored irrigation strategies are essential to align with local agroecological and hydrological conditions for optimal effectiveness and safeguarding long-term water security. Alternative agricultural and livelihood strategies need to be promoted to increase dry-season production and incomes in Nusa Tenggara and South Sumatra. Additional complementary household- and farm-level support is also necessary to achieve broader household welfare.
- Solar irrigation can strengthen water as well as food security when deployed under models that maintain positive marginal costs of pumping or allow electricity buy-back. Off-grid systems without governance safeguards risk increased groundwater extraction, posing depletion and ecological risks. Incorporating micro-irrigation technologies and pumping thresholds is essential to ensure solar irrigation adoption supports sustainable water use.

⁶ The research benefitted from the support from the Government of Indonesia: Ministry of National Development Planning (BAPPENAS), Ministry of Public Works and Public Housing, Ministry of Agriculture, and Ministry of Home Affairs, and the World Bank and the Project Management Unit for the Strategic Irrigation Modernization and Urgent Rehabilitation Project (SIMURP). Data collection research was supported by Lembaga Demografi, University of Indonesia. The chapter also benefitted from technical inputs drawn from the Solar Irrigation for Agricultural Resilience (SoLAR) program, funded by the Swiss Agency for Development and Cooperation (SDC).

5.1 Irrigation as a Key Water Infrastructure

Agriculture is one of the largest human interventions in the water cycle. Irrigation, land management, and crop choices shape how water moves through soils, rivers, aquifers, and the atmosphere, making resilient agricultural infrastructure essential to water cycle stability.

Irrigation systems are critical water infrastructures that support food production, climate resilience, and rural livelihoods, making them essential to agricultural stability under increasing climate pressures. Most parts of the world face greater rainfall volatility and an increased incidence of droughts, making irrigation infrastructure critical for maintaining crop yields and global food security [Walker and Van Loon (2023)]. By stabilizing the water supply, investments in irrigation rehabilitation can influence agricultural production and household well-being through multiple pathways.

First, improved access to irrigation can expand production by enabling farmers to cultivate additional land (extensive margin) [Dillon and Fishman (2019)]. Second, reliable irrigation enhances crop productivity by allowing farmers to increase the use of complementary inputs, such as fertilizers, thereby improving yields (intensive margin) [Duflo and Pande (2007); Bravo-Ureta et al. (2020)]. However, the effectiveness and adoption of irrigation can be constrained by factor market failures, such as limited access to inputs and labor market frictions [Jones et al. (2022)]. Finally, irrigation infrastructure contributes to climate risk adaptation by reducing vulnerability to water-related shocks, stabilizing yields, and thus improving farmers' livelihoods and well-being [Wang et al. (2024); Blakeslee et al. (2023); Domènech (2015)]. In other words, the welfare impacts of irrigation vary greatly depending on program formulation and implementation quality, institutional arrangements, and local socioeconomic and agroecological conditions.

Second, irrigation ultimately will still depend on the availability of water. Irrigation infrastructure reshapes local hydrology, influencing groundwater

recharge, evapotranspiration, and downstream flows. Here, there is also a risk that improvements in irrigation infrastructure can increase water use, speed up surface or groundwater depletion, and result in ecological risks. This chapter explores the impact of surface-water irrigation rehabilitation and solar-powered hydro pumps, across multiple sites in Indonesia and South Asia, respectively, to present some key lessons for such water infrastructure.

5.2 Indonesia Irrigation Rehabilitation

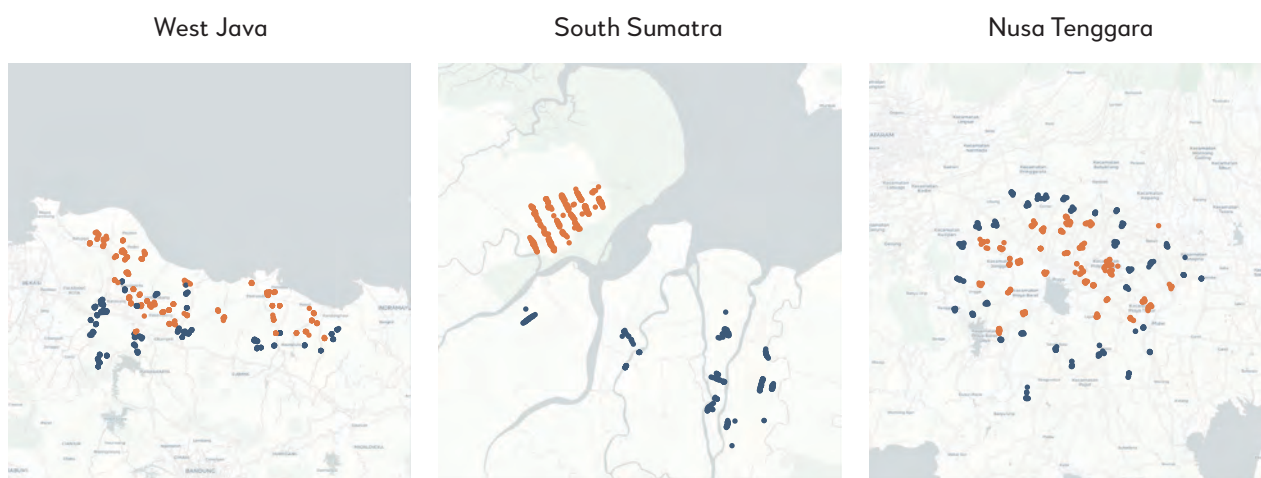
Irrigation systems in Indonesia face a range of challenges, including aging infrastructure, inefficient water delivery, and inter-sectoral competition for water, which often limit agricultural productivity.⁷ Given Indonesia's highly diverse agroecological zones and local water constraints, enhancing irrigation services through reliable, climate-resilient infrastructure tailored to local needs is critical to alleviating regional water constraints and boosting agricultural output, which is critical for socioeconomic well-being for millions of farm-households [Maccini and Yang (2009)].

The Government of Indonesia has thus prioritized large-scale investments in irrigation rehabilitation and modernization, as seen across three of the country's planning cycles (2015-2019, 2020-2024, and 2025-2029). The National Mid-Term Development Plan of 2019-2029 and 2020-2029 set a combined target of rehabilitating three million hectares of irrigated fields. The Strategic Irrigation Modernization and Urgent Rehabilitation Project (SIMURP) is designed to enhance performance and system resilience under changing climatic conditions by upgrading infrastructure in 14 irrigation schemes in Indonesia, covering a total land area of 276,000 hectares and reaching about 880,000 households.

The inclusion of diverse agroecological zones provides an opportunity to examine how SIMURP's investments perform in diverse production contexts.⁸ West Java illustrates the pressures of aging infrastructure serving an agroecologically favorable area amid increasing pressure of

⁷ An overview of irrigation challenges in Indonesia is provided here: *Transforming Lives Through Climate-Resilient Irrigation: Game Changers for a Livable Planet*.

⁸ For convenience and ease of reference, Jatiluhur is referred to as West Java, Jurang Batu and Sate as Nusa Tenggara, and Karang Agung as Sumatra throughout this chapter.

Figure 9: Survey Location of Sample, Treatment (Orange) vs Control (Blue)

Source: AIIF staff estimates.

land-use conversion and water competition driven by urbanization. Nusa Tenggara highlights the importance of irrigation systems in semi-arid production systems. Sumatra demonstrates the use of tidal irrigation infrastructure, which uses tidal water to manage water levels in low-lying coastal rice fields.

Production Characteristics Vary Substantially Across Agroecological Typologies

Detailed household survey data were collected in June 2025.⁹ To ensure comparability, beneficiaries from Water User Groups (WUGs) were randomly sampled, while non-beneficiary groups were identified in close collaboration with SIMURP's Project Management Unit. Figure 9 illustrates the geographic distribution of the sample for each region. Full details on survey instruments are provided in Appendix 1.

Jatiluhur Irrigation Scheme (JIS) in West Java spans approximately 240,000 hectares of predominantly paddy land under a double-cropping calendar. While wet-season cropping (October–April) benefits substantially from rainfall (~250–400 millimeters per month), dry-season production (May–September, with precipitation ranging between 90–130 millimeters per month) relies heavily on regulated releases from the Jatiluhur Reservoir,

which also supplies urban and industrial users in the Citarum Basin.

This dependence underscores that irrigation reliability is closely tied to upstream watershed conditions; reservoir sedimentation and upstream land management directly affect the availability of water for agriculture. Aging irrigation infrastructure, sedimentation, and increasing inter-sectoral competition for water further reduced the reliability of irrigation, negatively affecting agricultural productivity.

West Java demonstrates strong rice production performance across the two cultivation seasons, with the net value of production for an average farm being USD1,708 during the rainy season and USD1,656 during the dry season (Table 3). Rice yields across the two seasons do not differ as much as in other regions, as climatic conditions combined with the extensive irrigation system enable rice production throughout the year. The average landholding in the region is smaller compared to South Sumatra but larger than Nusa Tenggara.

In contrast, Nusa Tenggara exhibits a semi-arid production system, with production closely aligned with the monsoon cycle, reflecting marked wet and dry seasons. In the sample survey, paddy production dominates during the rainy months (~220–270 millimeters of precipitation per month),

⁹ This data was complemented by precipitation data from Global Precipitation Measurement (GPM) 07 [Huffman (2019)].

while households predominantly produce a mix of rice, soybeans, and tobacco during the dry season (with typically <40 millimeters of precipitation per month). Agricultural production remains highly dependent on hydrological conditions, leaving farmers vulnerable to monsoon variability and extended droughts. Nusa Tenggara records lower total production values, USD689 (rainy season) and USD636 (dry season), due to smaller landholdings in the region (0.35 hectares on average).

Meanwhile, lowland coastal regions of Indonesia, including South Sumatra, support substantial rice cultivation in an agroecology that is relatively unfavorable for rice production as compared to regions discussed above. However, areas affected by the tidal cycle, such as Karang Agung Hilir, are important for Indonesia's rice sector and the well-being of smallholder farmers [Rumanti et al. (2018)]. These areas rely on tidal irrigation, which uses the natural rise and falls of sea level to automatically flood and drain low-lying agricultural fields without mechanical pumping. The cropping calendar is closely tied to tidal cycles, with planting typically occurring during the rainy season (~250-280 millimeters of precipitation per month) when freshwater availability is highest.

Compared to other regions in the sample, rice production in the coastal South Sumatra relies on relatively abundant landholdings (Table 3). However, rainy season yields are lower than those of other production systems due to soil infertility and salinity in the coastal regions [Rumanti et al. (2018)]. Dry season production remains significantly muted in the absence of sufficient freshwater inundation and heightened salinity, which limit crop production in the region.

Overall, production is typically divided into wet and dry seasons in most parts of Indonesia. The specific months of the wet and dry seasons, and the intensity of the monsoon, vary considerably across regions (see above).

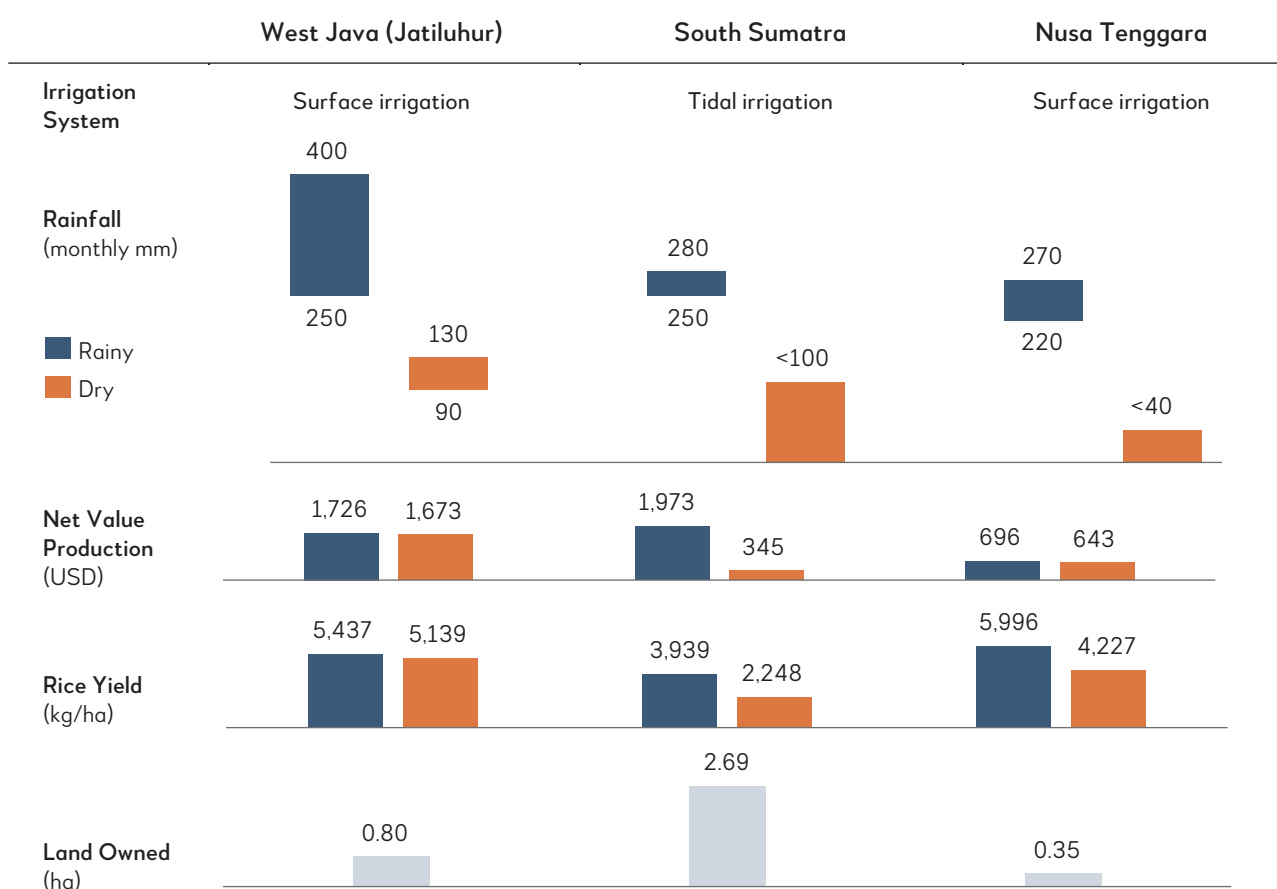
Variation in rainfall as well as El Niño events play a key role in determining the overall agricultural output, having significant impacts on welfare-related outcomes, including food security, health, and educational attainment [Maccini and Yang (2009)]. Meanwhile, irrigation infrastructure complements these tropical conditions and provides a buffer against high temperatures and irregular rainfall [Gatti et al. (2021)].

Impacts of Irrigation Rehabilitation on Farm Profitability

Using the Inverse Probability Weighted Regression Adjustment (IPWRA) estimator, the analysis reveals heterogeneous impacts of the SIMURP program across regions and seasons (Figure 10 and Figure 11).¹⁰ In Jatiluhur, the net value of agricultural production more than doubled during the dry season, suggesting significant profitability improvements associated with the rehabilitation program. In contrast, irrigation rehabilitations in South Sumatra and Nusa Tenggara are associated with gains of 35 percent and 24 percent, respectively. These gains are concentrated during the rainy season, with no impacts during the dry season. Notably, in South Sumatra, gains were primarily driven by expansion in cultivated area rather than improvements in land productivity. Conversely, in Nusa Tenggara, net value per hectare rose by 13 percent during the rainy season, and in Jatiluhur it doubled during the dry season. These point to regionally differentiated responses to irrigation rehabilitation.

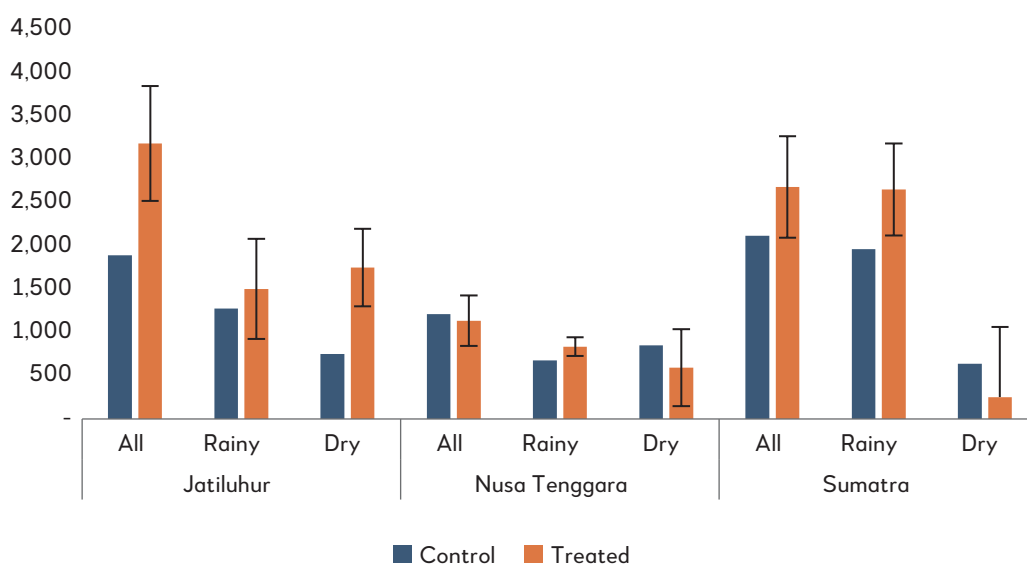
¹⁰ The survey employs ex-post cross sectional data. Because rehabilitation sites were not randomly assigned, simple OLS comparisons would likely suffer from endogeneity bias arising from systematic differences between beneficiary and non-beneficiary areas. To address this, the analysis uses the Inverse-Probably-Weighted Regression Adjustment (IPWRA) estimator, which combines inverse probability weighting (IPW) with regression adjustment (RA) in the second stage. The IPW stage re-weights the data such that the treatment are compared against a suitable counterfactual (treatment households under hypothetical non-treatment), reducing selection-bias. Then, in the RA stage, weighted regressions are used with a rich set of covariates to control for confounding. The identification is based on the conditional independence assumption or selection on observables, which assumes that after controlling for observables that explain selection into treatment, the treatment assignment is independent of potential outcomes.

Table 3: Production Diversity in Sample Sites

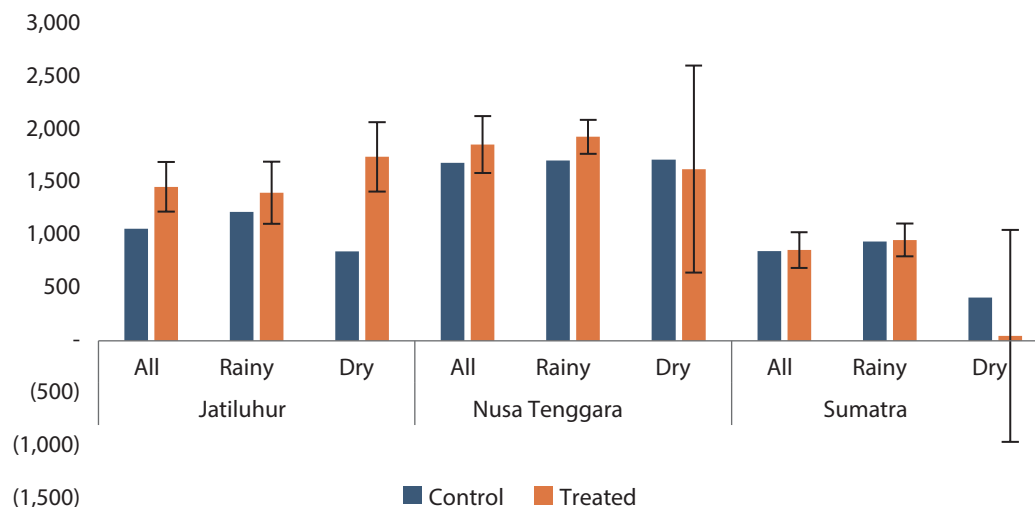


Source: AIB staff estimates from survey data. 1 IDR = 0.000065 USD. Notes: mm = millimeter; kg = kilogram; ha = hectare.

Figure 10: Impacts of Irrigation Rehabilitation on Net Value of Production (USD)



Source: AIB staff estimates.

Figure 11: Impacts of Irrigation Rehabilitation on Net Production Per Hectare (USD/ha)

Source: AIFB staff estimates.

Impact Channels

In Jatiluhur, irrigation rehabilitation is associated with increases in the net value of production through two channels: expansion of cultivated land, known as extensive margins, and increase in output per hectare, known as intensive margins (Figure 12).

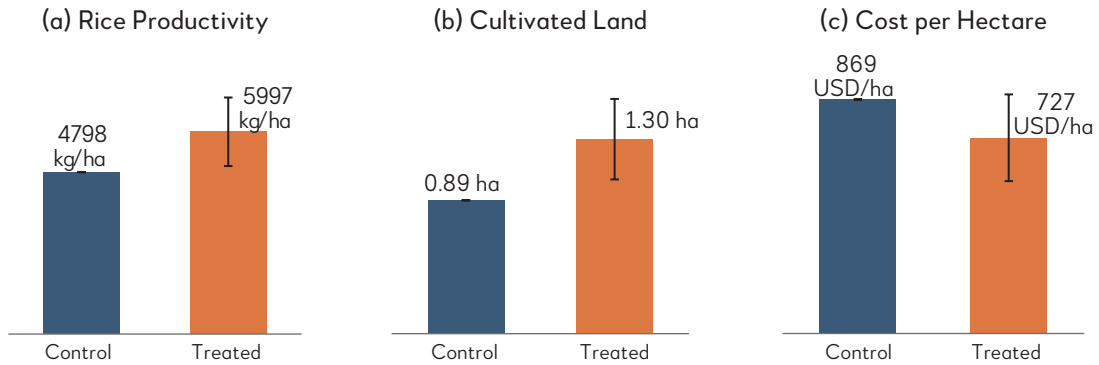
The project was associated with a 46 percent increase in cultivated land during the dry season as compared to the control group (extensive margin). Improved water delivery allows farmers to reclaim land that was either permanently or intermittently abandoned due to insufficient water availability. Furthermore, rice yields in the treatment group improved by 25 percent due to reliable irrigation and water delivery during the dry months (intensive margin). Overall, rehabilitation was associated with a 16 percent reduction in costs per hectare. These improvements in cost efficiency were mostly due to reductions in labor costs per hectare, as better infrastructure reduced manual effort associated with water management, boosting overall returns from farming.

In contrast, the effects of irrigation rehabilitation were concentrated mainly on the intensive margin in Nusa Tenggara, as additional land cultivation was constrained by small landholdings. There was an increase of five percent in rice yields and a decrease of 16 percent in costs per hectare, but these gains were observed only during the rainy season (Figure 13). In South Sumatra, like Nusa Tenggara, the positive effects of irrigation rehabilitation are concentrated during the rainy season, as dry-season agriculture is practiced by only a few households in the sample due to drought and salinity concerns in the region. However, in contrast to Nusa Tenggara, the impacts accrue due to a 30 percent increase in land cultivation as compared to the control group, since land is not a binding constraint.¹¹

These results highlight the importance of regionally differentiated irrigation policies. In agroecologically favorable areas such as Jatiluhur, which also have better complementary infrastructure across the agricultural value chains, irrigation rehabilitation can generate substantial gains through both extensive and intensive margins, supporting the case for scaling such investments where dual-season rice cultivation is viable. In contrast, in regions like Nusa

¹¹ In the case of South Sumatra, while the control group consists of tidal irrigation and rice production, some of these villages were part of the national transmigration program initiated in the 1970s, which may have been allocated better land. Moreover, older tidal irrigation schemes tend to improve land suitability over time, which can lead to increasing agricultural yields [Setiawan et al. (2021)]. Consequently, the control group may have had inherently more favorable conditions for rice yields that are unrelated to the current rehabilitation. This suggests that the rehabilitation effects for the treated group may be conservative, and the true effects of irrigation rehabilitation could be even higher.

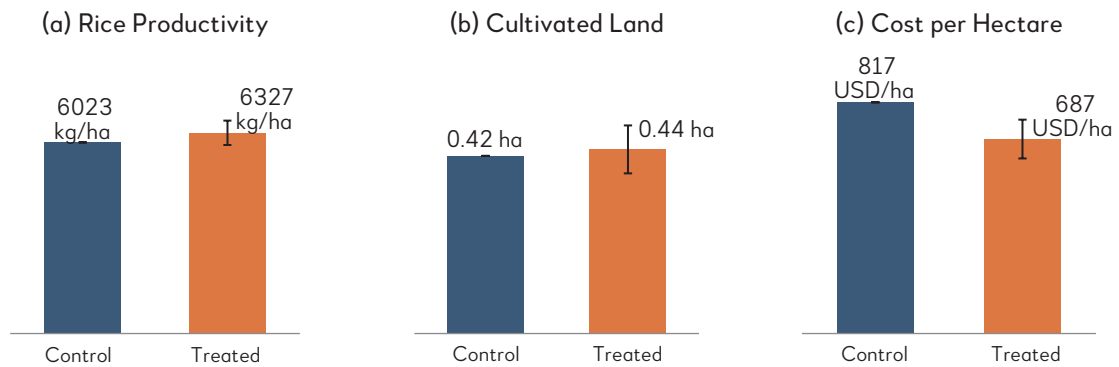
Figure 12: Irrigation Rehabilitation Increases Productivity, Cost Efficiency, and Land Use During the Dry Season in West Java



Notes: kg = kilogram; ha = hectare.

Source: AIB staff estimates.

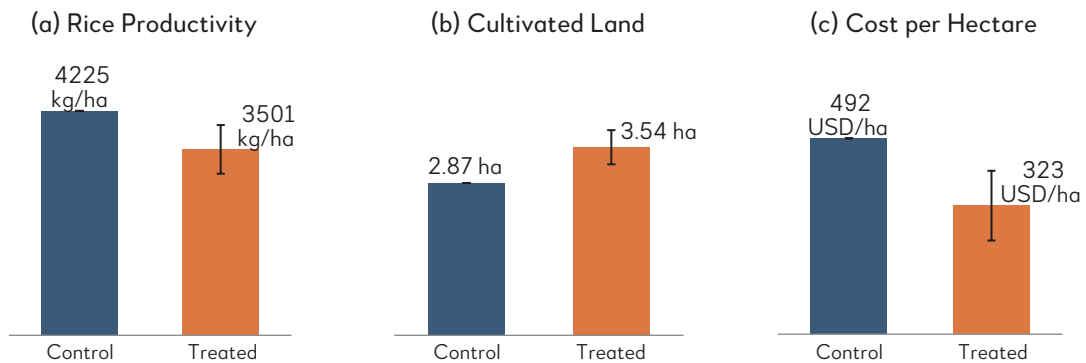
Figure 13: Irrigation Rehabilitation Increases Productivity and Cost Efficiency During the Rainy Season in Nusa Tenggara



Notes: kg = kilogram; ha = hectare.

Source: AIB staff estimates.

Figure 14: Irrigation Rehabilitation Increases Cultivated Land and Cost Efficiency During the Rainy Season in South Sumatra



Notes: kg = kilogram; ha = hectare.

Source: AIB staff estimates.

Tenggara and Sumatra that face limitations due to agroecological conditions, policy should focus on enhancing seasonal productivity through targeted support for crop diversification, adoption of climate- and drought- and salinity-tolerant varieties, and alternative, decentralized water infrastructure such as rainwater harvesting. Recognizing these regional differences is essential for maximizing the impact of irrigation investments and ensuring inclusive agricultural growth.

While irrigation infrastructure can boost agricultural output, it also raises water demand, placing additional pressure on reservoirs. Therefore, sound policies governing irrigation systems are critical to ensure sustainable water use. The next section explores sustainable deployment models for solar irrigation infrastructure, highlighting the role of economic incentives in promoting long-term groundwater sustainability.

5.3 Sustainable Models of Solar Irrigation: Lessons Learned from South Asia

Besides surface-water irrigation infrastructure, groundwater-based infrastructure is also a key source of water support for agriculture, especially in South Asia. In recent years, solar-powered irrigation has expanded rapidly in South Asia, driven by falling photovoltaic costs, unreliable grid supply, rising diesel prices, and generous subsidies [Ministry of New and Renewable Energy (2025); IRENA and FAO (2021)]. Because solar pumps offer reliable daytime power with nearly zero operating costs, they are increasingly viewed as a cornerstone of climate-smart agriculture [Buisson (2024); Varshney (2025)].¹²

Yet a persistent concern is that cheap energy may lead to excessive groundwater extraction, a risk frequently attributed to solar technology itself [Balasubramanya (2024); Closas and Rap (2017)]. However, evidence from the International Water Management Institute (IWMI) shows that solar irrigation is not inherently unsustainable. What matters is the deployment model and, more

specifically, the economic incentives embedded within each model. These deployment models are context-specific, depending on local groundwater conditions, farming systems, and policy settings, the same technology can either drive extraction behaviors or incentivize water-efficient use [Alam et al. (2025)].

The central insight emerging from the literature is that groundwater impacts are shaped by how each solar irrigation model alters the marginal cost of pumping. In South Asia's largely unregulated aquifer systems, marginal cost strongly influences irrigation timing, cropping choices, and total extraction [Shah (2009); Mukherjee (2018)].

Off-grid models, grid-connected models, feeder-solarized systems, fee-for-service arrangements, and irrigation-as-a-service systems each affect this cost differently. As a result, they create distinct behavioral pathways that explain why groundwater outcomes vary widely across regions and programs.

Off-grid solar pumps, which are the most widely adopted model in India, Pakistan, and Nepal, reduce the marginal cost of pumping to nearly zero. Because farmers cannot sell unused electricity and face no per-unit pumping cost, they irrigate as long as marginal benefits remain positive. This often results in longer pumping hours, expansion of irrigated area, and shifts toward more water-intensive crops [Gupta (2019); Shah (2018)].

Empirical studies consistently document increased extraction following off-grid adoption, although most rely on proxies such as irrigation hours or energy use rather than direct aquifer measurements [Balasubramanya (2024)]. To mitigate these risks, off-grid systems require explicit institutional and technological safeguards, such as collective groundwater management rules, crop water budgeting, adoption of technological controls, e.g., drip and sprinkler systems, and the installation of a pump cut-off threshold or flow restrictors, to limit over-pumping.

Grid-connected solar pumps introduce a vastly different dynamic because farmers can export surplus electricity to the grid at a feed-in tariff.

¹² For example, AIB is providing finance to support the state of Maharashtra in India for climate resilient distributed off-grid solar power pumps for irrigation. This can reduce dependence on fossil fuels. Pumps are permitted only where groundwater extraction is within safe limits. Technical safeguards such as borewell depth limits and pump capacity limits are put in place.

Evidence from Gujarat's SKY program, studied by IWMI, shows that this mechanism reduces irrigation energy use during high-demand seasons without harming yields [Shah (2018); Varshney (2025)]. When income from exporting electricity exceeds the expected return from irrigation, farmers rationally conserve groundwater. The feed-in tariff of electricity essentially becomes the shadow price of water, turning solar electricity into a remunerative output and making solar irrigation more compatible with groundwater sustainability objectives. However, the scalability of this approach remains uncertain.

Feeder-level solarization, common in Maharashtra and several Indian states, supplies agricultural feeders with solar-generated power while keeping farmer tariffs unchanged. Because marginal cost for users remains the same, groundwater use does not substantially increase. Studies from Maharashtra indicate improved reliability and voltage stability but no significant change in irrigation volumes or cropping patterns [IWMI (2023)]. This model decarbonizes rural power supply without creating new extraction pressures, making it a low-risk pathway for large-scale renewable integration.

In **fee-for-service models**, most notably Bangladesh's IDCOL program, farmers pay volumetric or time-based fees for irrigation water. Although the solar energy itself is costless, the pricing structure reintroduces a positive marginal cost, which encourages farmers to use water more carefully [Mitra et al. (2021); Buisson (2024)]. Service providers, however, must recover capital costs and, therefore, have incentives to maximize sales during peak seasons. This can increase extraction pressures in high-demand cropping zones.

Irrigation-as-a-service models such as those used by Oorja Solutions in India follow similar principles. Farmers purchase water rather than pumps, thereby eliminating upfront capital requirements and expanding access for smallholders. Volumetric pricing and metering help promote efficient irrigation, and early evidence shows reduced diesel use, lower costs, and yield gains [Oorja Development Solutions (2024)]. Although these models are commercially attractive and supportive of smallholders, long-term groundwater effects are not yet well documented, and provider incentives may still favor regions with high water demand.

These patterns demonstrate that the model's incentive structure, rather than the solar technology itself, exerts pressure on groundwater. Across all models, a recurring limitation in the empirical literature is the reliance on indirect indicators of groundwater use, the short duration of most studies, and the limited integration of hydrological and institutional context. As a result, long-term sustainability remains uncertain even when behavioral effects are well understood.

5.4 Concluding Remarks

Effective irrigation and agricultural water management are essential for food production, climate resilience, and rural livelihoods. The SIMURP experience demonstrates the positive impact of irrigation but also highlights the limitations posed by agroecological and hydrological realities, climate variability, and local institutional environments. West Java recorded a doubling of the net value of agricultural production, highlighting the potential for significant gains in ecologically favorable areas.

However, in Nusa Tenggara and South Sumatra, the benefits were concentrated during the rainy season, with dry-season gains limited by factors such as drought and salinity. These findings underscore the necessity of tailoring irrigation strategies to local agroecological realities and aligning irrigation projects to the hydrology that feeds them.

In addition, the study also highlights the need for infrastructure investments to be complemented by nutrition-sensitive interventions, such as crop diversification and nutrition education, to improve household welfare. Policymakers should prioritize context-specific modernization of irrigation systems, address factor market failures, and integrate farm-level support, such as access to improved inputs and adaptive training, to maximize the effectiveness of irrigation projects and promote water security and resilient rural development.

For solar powered hydro pumps, the emerging consensus from South Asia shows that the sustainability of solar irrigation depends on aligning economic incentives with groundwater stewardship. Models that create opportunity costs, preserve existing tariffs, or reintroduce positive marginal costs tend to moderate extraction. However, the

scalability of these models remains limited with off-grid systems dominating the market in South Asia. Off-grid systems pose the greatest risk of increased pumping when technological and institutional safeguards are absent. Ensuring that solar irrigation supports water-saving outcomes, therefore, depends not on the technology itself, but on the rules, tariffs, and incentives that govern its use.

To sum up, resilient agriculture depends not only on farm-level infrastructure but on maintaining the integrity of the wider water cycle that sustains rainfall, soil moisture, and groundwater resources. Designing irrigation systems that work with the water cycle is therefore central to long-term agricultural resilience and human welfare.

Box C: Leveraging Water Investments to Empower Marginalized Groups

Social inclusion is a critical consideration in agricultural water management, as marginalized groups, including women, landless farmers, and the poor, often face unequal access to water resources and decision-making structures. Droughts and floods often exacerbate existing gender inequalities, affecting women and girls more severely. Evidence from India links rainfall shocks to increased violence against women, while in Central Asia, female farmers remain at the greatest risk of lacking access to irrigation water and of being underrepresented in water user organizations [Sekhri and Storeygard (2014); Balasubramanya (2019)].

In Pakistan, poor sanitation facilities in schools deter adolescent girls from education: Up to 50 percent of girls do not attend school during menstruation [Young et al. (2019)]. These examples highlight the complex and multifaceted connections involving water, gender, and inequality. Water investments will not deliver their expected benefits and services unless such dimensions are recognized and incorporated [Resurreccion et al. (2019); Das and Hatzfeldt (2017)].

Evidence from Ongoing Investments

The Asian Infrastructure Investment Bank's West Bengal Major Irrigation and Flood Management Project in India demonstrates how gender considerations can be systematically embedded in irrigation investments. During project preparation, consultations with women and men in the project areas informed the development of gender action plans and led to gender-specific implementation.

Implementation has focused on two fronts. First, within public institutions, the project supports capacity-building for female engineers in the Irrigation and Waterways Department. Training programs enhance women's technical competency in Geographical Information Systems, environmental and social safeguards, and procurement. The project also seeks to increase the number of female engineers through dedicated recruitment, reflected directly in the project's output indicators.

Second, at the community level, the project institutionalizes women's participation by ensuring representation on Grievance Redress Committees. One-third of seats in each of the 396 committees are reserved for women, typically sourced from local women's self-help groups. This ensures that women's voices shape the resolution of irrigation service delivery issues, moving beyond token participation toward greater influence in decision-making.

The Indonesia Strategic Irrigation Modernization and Urgent Rehabilitation Project also demonstrates another example of gender-responsive design. From the outset, the project set a target to increase women's participation in water user associations and related decision-making roles such as crop planning and irrigation scheduling. Through public advocacy, partnerships with women's farmer groups (Kelompok Wanita Tani), and female-focused training programs, the project exceeded its goals: Women's participation rose to 90 percent, surpassing the target of 50 percent. The training activities combined technical modules with income-generating skills, such as seedling production, organic pesticide production, composting, and post-harvest processing.

Outlook and Way Forward

Water investments could be a powerful tool to address economic and gender inequality. However, projects must be designed with a careful balance between infrastructure and socioeconomic improvements, alongside meaningful participation of women and marginalized groups. In other words, the development impact of infrastructure projects could be augmented when they are specifically designed to benefit marginalized groups. Regular and comprehensive reviews of the impact of public investments on addressing wealth and gender inequalities will be central to establishing and continuously updating the relationship between expenditures and desired outcomes—and to refining future expenditures to optimize their impacts.



CHAPTER 6

IMPACT OF FLOODS DAMAGES TO LIVES, PROPERTY, AND IMPACT ON WATER QUALITY

HIGHLIGHTS

- Flooding events have become more frequent and intense, leading to widespread loss of lives and properties. Floods also significantly affect water quality with health and ecological consequences. This study on global flood events shows immediate spikes in suspended sediments and delayed yet persistent increases in algal biomass following the event.
- Agricultural landscapes are the primary source of flood-related water-quality deterioration. Catchments dominated by agriculture show extremely large sediment surges, clear phosphorus pulses, and high volatility in nitrogen and organic pollution, patterns driven more by agricultural management practices than by floods alone. This is particularly relevant to developing economies with large agricultural populations, with health vulnerabilities.
- Forests are key to water quality, protecting against floods through their water absorption capacity and providing exceptional natural resilience to flood-related water pollution. They are a key defense against hydrological extremes. Forest conservation and restoration are critical.
- Land use determines watershed vulnerability under climate change. As extreme rainfall events intensify, nature-based solutions, especially forest conservation and watershed protection, will be critical for preserving water quality, while targeted improvements in agricultural management are essential for mitigating flood-driven pollution risks.

6.1 Introduction: Climate Change and Floods

Floods represent one of the most visible expressions of water cycle disruption. Climate change is reshaping the global water cycle, increasing both the volatility of water availability and the severity of water-related hazards. Floods have become one of the most frequent and destructive natural disasters globally, accounting for 44 percent of all disaster events between 2000 and 2019 and affecting 1.6 billion people—the highest of any disaster type [UNDRR (2020)]. Over the past two decades, the frequency of very large and extreme flood events has increased markedly, as illustrated in Figure 15.

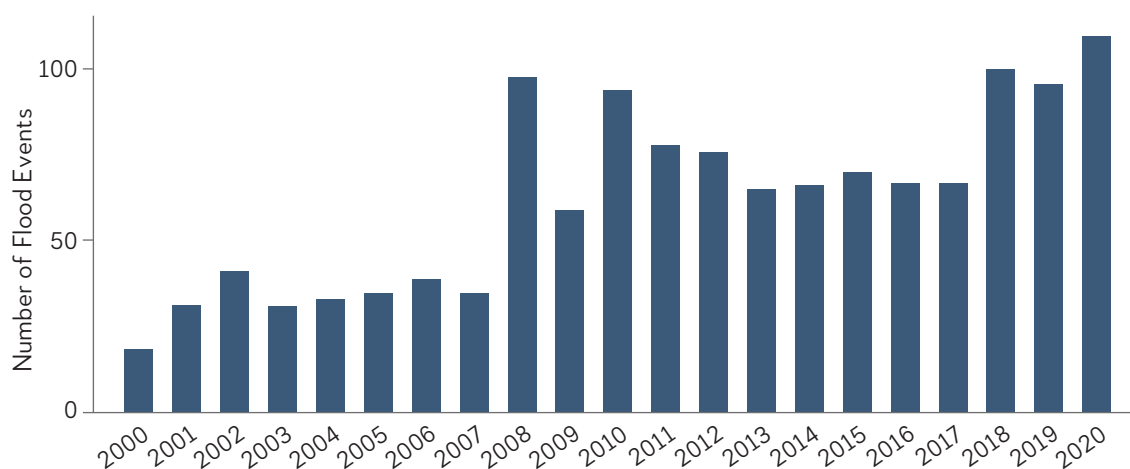
In many economies, particularly across Asia, recent years have seen repeated episodes of severe flooding that destroy homes and critical infrastructure, disrupt transport and energy systems, and displace large populations. These events can wipe out years of accumulated household assets, undermine local business activity, and place additional pressure on already constrained fiscal and institutional systems.

The immediate human consequences of floods are severe. High water levels, rapid-onset flash floods, and landslides cause acute health emergencies. Once the flood peak passes, prolonged displacement, overcrowded shelters, and damaged infrastructure

create a second wave of risks. Destroyed roads and bridges impede access to schools, markets, and health care facilities. Damaged power and communication networks hamper emergency response and recovery. Given their disruptions to agriculture, floods also have a large negative impact on incomes and food security. Vulnerable groups, including children, older persons, women, persons with disabilities, and low-income households, are disproportionately exposed and have the least capacity to recover, making floods powerful amplifiers of existing socioeconomic inequalities [UNICEF (2023)]. Box D: Economic Impact of Floods and Subsequent Recovery. Evidence from South India following this chapter presents the findings of post-flood household income and expenditure dynamics in India, highlighting the impact floods have on production and welfare.

Floods also generate far-reaching health impacts that extend beyond the immediate disaster period. When floodwater overwhelms drainage systems and damages water and sanitation infrastructure, sewage overflows, and contamination of drinking-water sources trigger outbreaks of diarrheal disease, cholera, typhoid, and leptospirosis. Standing water left behind as floods recede becomes a breeding ground for mosquitoes, contributing to higher cases of dengue and malaria [AIIB (2025)]. These health impacts translate into sizeable economic losses.

Figure 15: Number of Very Large and Extreme Flood Event—2000–2020



Notes: Very large events: with a greater than 2 decades but less than 100 year estimated recurrence interval, and/or a local recurrence interval of at 1-2 decades and affecting a large geographic region (> 5000 sq. km).

Extreme events: with an estimated recurrence interval greater than 100 years.

Source: The Dartmouth Flood Observatory (DFO).

6.2 Impact of Floods on Water Quality Shocks

Ironically, water quality itself is almost certainly severely affected by floods. Floods act as powerful conveyor belts, translating upstream land-use structure and pollution hazards into acute water-quality shocks. Intense rainfall and overbank flows mobilize sediments, nutrients and contaminants stored in soils, riverbeds, and floodplains, often pushing concentrations beyond regulatory thresholds over short time horizons. These dynamics unfold over days to weeks, precisely when human exposure and system stress are highest, yet they are often obscured in annual or seasonal averages.

The economic and social consequences are significant. Degraded water quality is associated with increased diarrheal disease burdens, child stunting, reduced labor productivity, and substantial declines in agricultural output. For instance, evidence shows that when Biological Oxygen Demand exceeds critical thresholds, GDP growth in downstream regions falls by one-third, illustrating how water-quality degradation directly constrains economic performance [Damania (2019)].

A substantial body of empirical work shows that upstream land-use patterns matter. Impervious surfaces and cropland amplify stormwater runoff and pollutant concentrations, while forests and wetlands moderate peaks through infiltration, storage, and nutrient uptake [Allan (2004); Foley (2005); Tong and Chen (2002); Weller (2011); Zhang et al. (2022)]. At the global scale, Chung et al. (2021) find that protected wetlands sustain freshwater provision while forest cover in protected areas enhances sediment regulation and hydropower production, though flood mitigation depends primarily on reducing impervious surfaces and expanding urban green spaces. Meta-analyses confirm the negative association between forest cover and nutrient loads, and the positive elasticity for agricultural intensity [Ahearn (2005)].

Research on climate extremes and urban water management further shows that floods often trigger combined-sewer overflows, treatment plant failure, and short-term contamination episodes that threaten public health [Li et al. (2021); O'Donnell

(2021)]. However, this infrastructure-centric view often overlooks upstream ecosystem responses that mediate how climate extremes translate to downstream water quality. Most existing case studies do not incorporate an explicit upstream land-use or ecosystem lens, limiting understanding of how natural infrastructure modulates climate-driven water-quality extremes at the watershed scale.

Two empirical limitations further constrain the evidence base. First, existing analyses suffer from temporal masking: most rely on annual or seasonal means that blur the short-lived yet consequential pollution peaks and recovery trajectories following flood events. Second, limited external validity: evidence thus far consists of small-sample, site-specific studies, often confined to particular river basins or governance settings. These studies are highly valuable and relevant for local policy actions, but their contextual specificity makes it more difficult to distil broader, cross-regional patterns.

To advance the evidence base, this chapter quantifies these dynamics at the global scale using a harmonized station-event panel that integrates hydrological, land use, and water-quality data. Land use is treated not as a background control, but as a structural determinant that governs runoff generation, pollutant mobilization, and recovery-independent of specific project assets.

6.3 Methodology and Data

The analysis employs an event-study framework with staggered treatment timing. This enables the tracing of dynamic treatment effects before, during, and after floods while controlling for unobserved spatial heterogeneity and common temporal shocks. A key strength of the event-study approach is its ability to recover the full temporal profile of water-quality responses, capturing both the sharp rise in pollutant concentrations during flood peaks and the subsequent decay as rivers return toward baseline conditions. This is particularly important because the magnitude and persistence of post-flood contamination cannot be adequately captured by simple before-after comparisons. The full methodology is described in Appendix 2.

Water Quality Data. Water-quality information is sourced from the Global Environment Monitoring System for Water (GEMStat). The dataset aggregates harmonized in-situ water-quality measurements reported by national agencies and research networks, offering the most geographically comprehensive and temporally consistent public dataset for freshwater quality. The analysis draws on 14,391 monitoring stations across 61 countries, with an average reporting frequency of two observations per week, forming a balanced panel of over 20 million station-day observations between 2000 and 2020.

The study focuses on six core indicators that capture major pollutants: 1) Total Suspended Solids (TSS): sediment loads and turbidity; 2) Total Phosphorus (TP): eutrophication potential; 3) Total Nitrogen (TN): nutrient loading; 4) Biochemical Oxygen Demand (BOD): organic pollution and microbial activity; 5) Chemical Oxygen Demand (COD): total oxidizable organic load; and 6) Chlorophyll-a (Chl-a): proxy for algal biomass and eutrophication. These indicators represent the principal biogeochemical dimensions of water quality most sensitive to hydrological shocks [Meybeck (2003); Damania (2019)].

Figure 16 maps the spatial distribution of the GEMStat monitoring network. Coverage is densest in Europe, North America, and parts of East Asia, with substantial representation across Latin America. By contrast, large gaps remain across much of Sub-Saharan Africa and the Middle East. While South and Southeast Asia host some monitoring stations, coverage remains limited relative to the high incidence of flood events shown in Figure 17.

Flood Event Data. Flood characteristics are obtained from the Dartmouth Flood Observatory (DFO)'s Global Active Archive of Large Flood Events. Events are defined as spatially contiguous inundated areas that persist for at least 24 hours, with severity indexed by affected area, depth, duration, and socioeconomic impacts.

The DFO database documents approximately 5,000 flood events between 1985 and 2024, of which 3,577 events fall within our analysis window (2000-2020). Station-event pairs are constructed by intersecting monitoring station coordinates with flood polygons and restricting the sample to symmetric pre- and post-flood observation windows (± 8 weeks).

Figure 16: Distribution of Water Quality Monitoring Stations

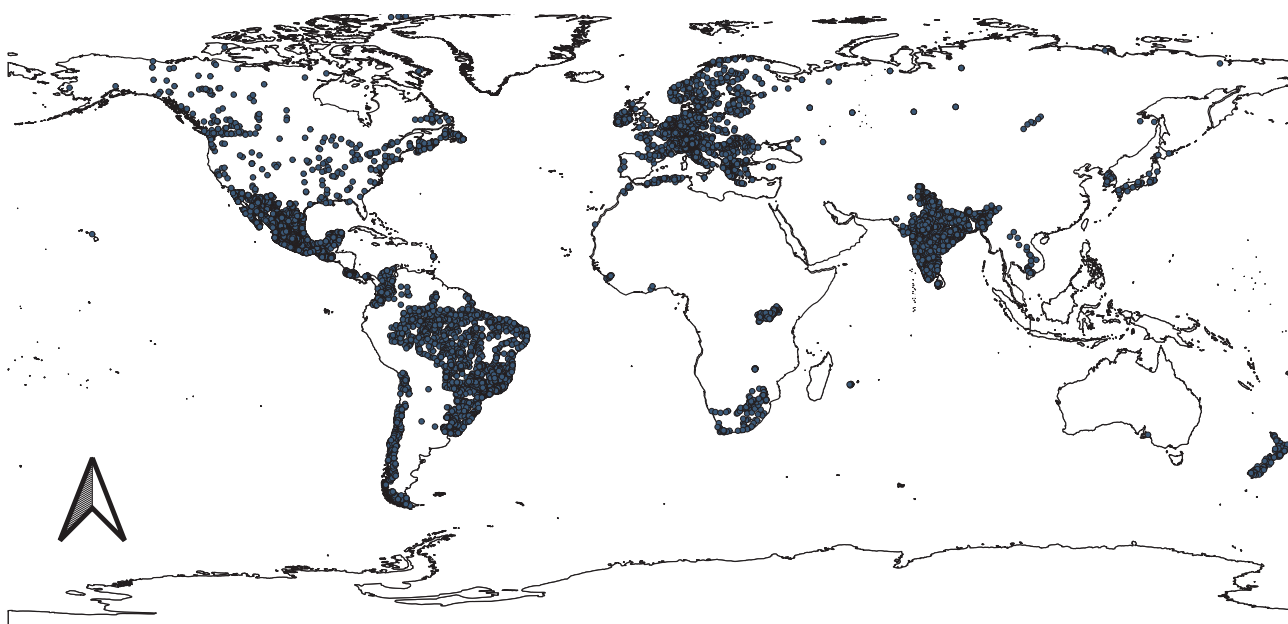
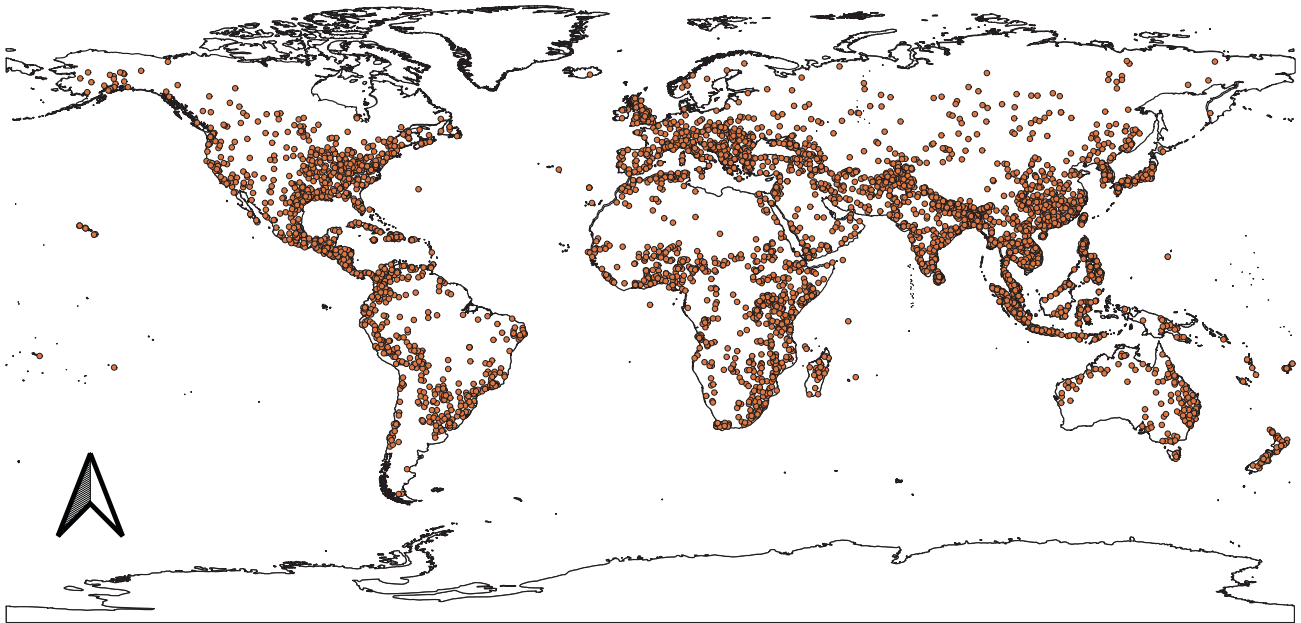


Figure 17: Distribution of Flood Events



Source: The Dartmouth Flood Observatory (DFO).

Overlapping or recurrent events are trimmed to avoid double-counting, and robustness checks are conducted for alternative window lengths. Figure 17 shows the global distribution of major flood events, revealing high concentrations in South and Southeast Asia, Eastern Africa, and South America. The juxtaposition of these figures highlights a pronounced spatial mismatch between hydrological risk and water quality monitoring capacity, motivating our focus on station–event matching. Importantly, flood events are identified independently using satellite-based data and disaster records from the DFO, ensuring that flood detection is not influenced by the presence of monitoring stations.

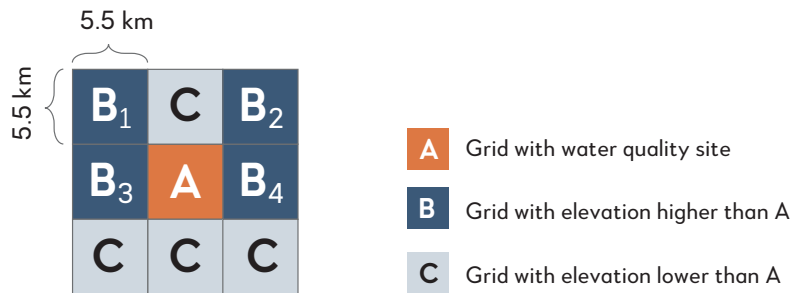
Upstream Land-Use Composition Data.

Upstream land-use patterns are derived from the European Space Agency Climate Change Initiative land-cover dataset between 1992 and 2022. The analysis focuses on three primary land-use categories at sub-kilometer resolution: 1) Urban areas: impervious surfaces, roads, and settlements;

2) Agricultural land: intensive and extensive cropland areas; 3) Forest: evergreen and deciduous canopy cover.

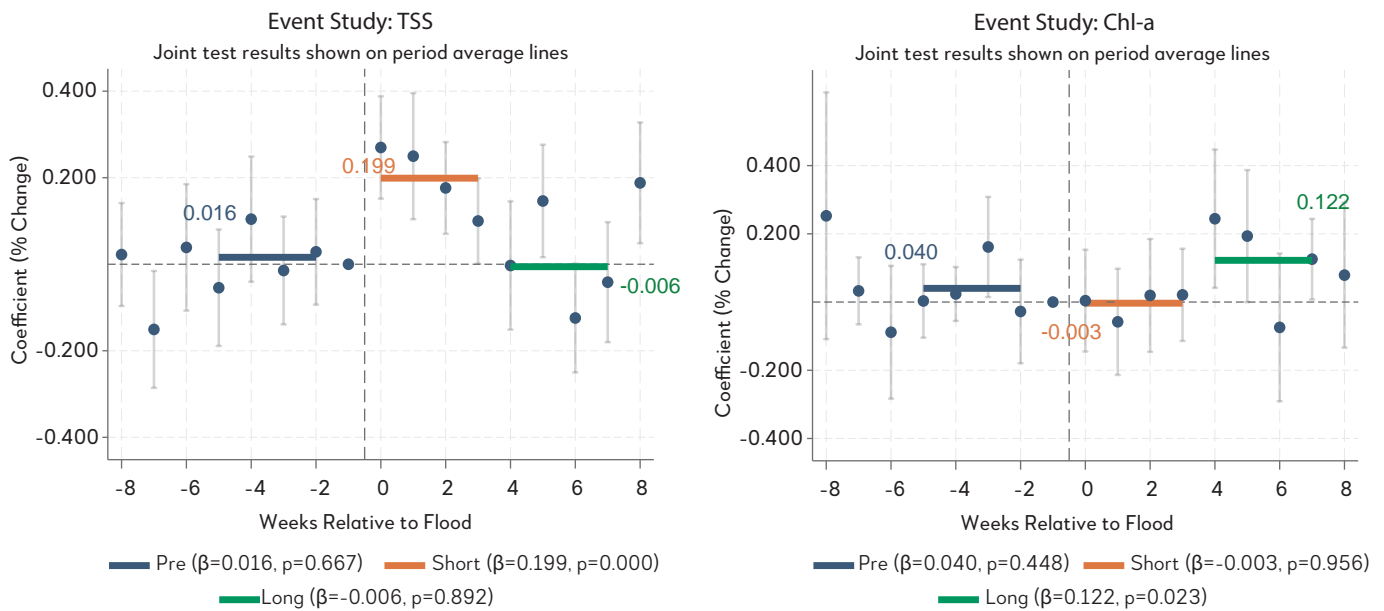
Elevation data. Topographic delineation of upstream catchments is conducted using the GTOPO30 global digital elevation model (USGS), at a spatial resolution of one square kilometer. For each monitoring station, an upstream buffer is delineated based on elevation gradients and flow direction. As illustrated in Figure 18, the procedure is as follows: 1) Assign each station to a 5.5 kilometer × 5.5 kilometer grid cell (grid A, representing the “local” area); 2) Identify eight surrounding grid cells as neighboring regions (grids B–I); 3) Compare elevation values: Neighboring grids with higher elevation than grid A are classified as upstream contributors (group B), while lower-elevation grids (group C) are excluded; 4) Compute the share of each land-use type among the upstream contributors, forming land-use composition indicators. This approach approximates local drainage connectivity where full hydrological routing data are unavailable, enabling consistent global coverage.

Figure 18: Illustration of Upstream Land-Use Delineation



Source: AIIB staff illustration.

Figure 19: Event Study Estimates for TSS and Chl-a



Source: AIIB staff estimates.

6.4 Results: Post-Flood Water Quality Dynamics

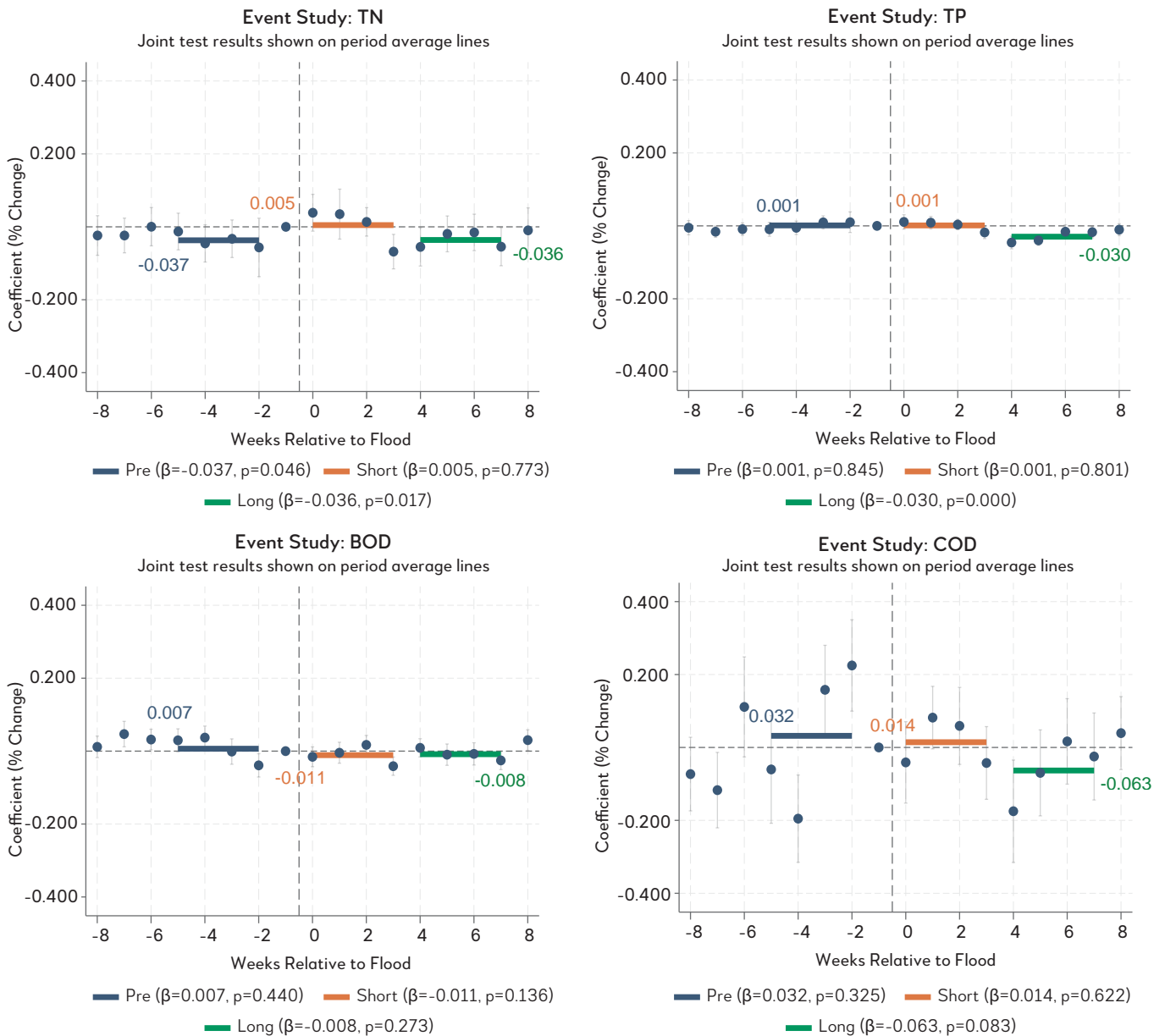
Baseline Results

Results suggest that floods generate statistically significant increases in suspended sediment (TSS) and algal biomass (Chl-a), but with distinct temporal patterns. On average, TSS rises by approximately 20 percent within four weeks following a flood event [Figure 19, left panel]. This is consistent with hydrological evidence showing that floods intensify erosion and sediment mobilization in both rural settings [Carroll et al. (2004)] and urban environments [Brown and Chanson (2012)]. High-intensity rainfall events

and floods result in increased erosion, mobilization and re-suspension of sediments from a range of sources, such as in-stream, floodplain, and broader catchment [Van Vliet et al. (2023)]. The effect dissipates relatively quickly at around four weeks after the flood.

For Chl-a, an indicator of eutrophication risk and algal biomass, a positive and statistically significant increase appears around four weeks after the flood [Figure 19, right panel]. This confirms insights from the water quality literature showing that algal bloom formation is not instantaneous following a flood and that algal blooms show a lag effect after antecedent flood changes and related nutrient influx [Liu et al. (2022); Irani Rahaghi et al. (2024)].

Figure 20: Event Study Estimates for TP, TN, BOD, and COD



Source: AIIIB staff estimates.

In contrast to TSS and Chl-a, nutrient indicators (TN, TP) and organic-load metrics (BOD, COD) show mixed responses to flood shocks (Figure 20). Overall, these indicators display a ‘flushing out’ effect of floods, whereby concentrations tend to decline in the weeks following the flood event.

On the one hand, floods can lead to greater mobilization of these pollutants, for example, when fertilizers (N and P) not absorbed by plants accumulate in soils and are then mobilized by runoff during a flood. On the other, floods also mean higher dilution rates, so overall concentrations tend

to decline afterward. The balance of these opposing forces results in the muted or slightly negative responses observed in our estimates, consistent with findings from the hydrological literature [Van Vliet et al. (2023)].

Heterogeneity and Mechanisms

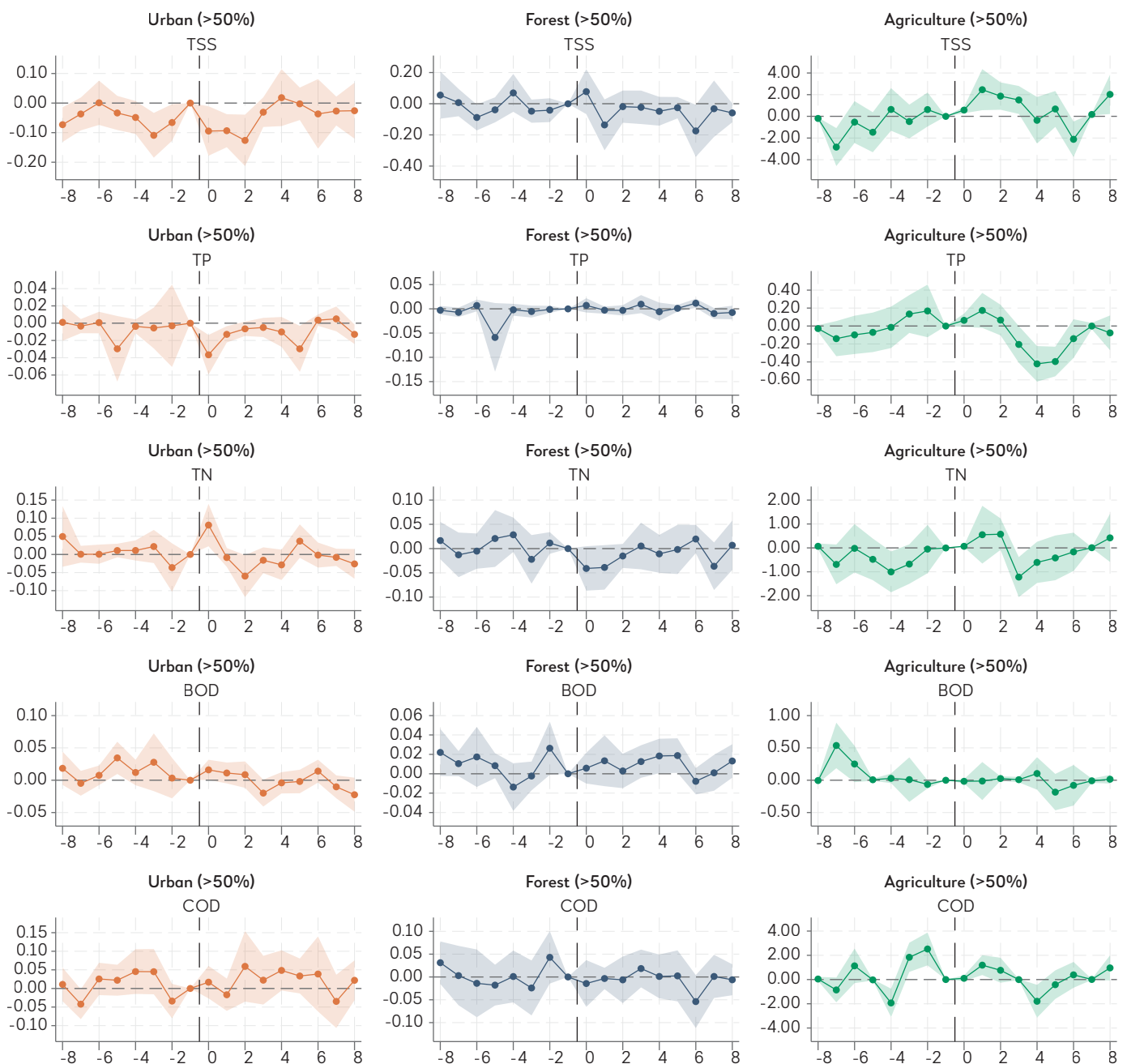
Further research reveals distinct differences in water-quality dynamics across upstream land-use types, including urban-, forest-, and agriculture-dominated catchments (Figure 21).

Sediments (TSS). In forest-dominated and urban catchments, there were only modest changes in sediment loads (generally within ± 10 percent). Forested areas provide strong natural protection: Deep root systems stabilize soils, while canopy cover reduces raindrop impact and surface erosion, resulting in near-flat TSS responses. Urban areas, characterized by impervious surfaces

and engineered drainage systems, also show limited additional sediment mobilization even during heavy rainfall. By contrast, agriculture-dominated catchments exhibit extremely large TSS spikes in the one to three weeks following floods, with log coefficients of 2-3 (equivalent to 200-300 percent increases). Cropland soils are often exposed and highly erodible; ploughed fields,

Figure 21: Heterogeneous Event-Study Estimates for TSS

Heterogeneous Event Study by Dominant Land Use (>50%)



Notes: Rows: Parameters (TSS, TP, TN, BOD, COD); Columns: Urban/Forest/Agriculture.
Source: AIIB staff estimates.

bare soil, and artificial drainage channels facilitate rapid sediment transport into rivers. Consequently, floods mobilize large volumes of sediment in agricultural landscapes, producing pronounced and persistent post-flood sediment pulses.

Total phosphorus (TP). Similarly, TP effects are essentially flat for forests with no measurable flood-induced changes. This reflects the strong natural buffering capacity of forests—root systems stabilize soils, and canopy and litter layers limit overland flow and sediment detachment. Urban catchments also show small and statistically weak TP responses. In contrast, agriculture-dominated catchments exhibit much stronger and more variable TP dynamics. Fertilizer application, exposed soils, and shallow overland flow can elevate TP levels both before and immediately after the flood peak. A clear TP increase of roughly 20 percent emerges in the first few weeks following flood onset, indicating substantial mobilization of particulate phosphorus from fertilized or recently disturbed soils. In the weeks that follow, TP concentrations decline, reflecting the combined influence of dilution and the settling of particulate phosphorus after the flood.

Total nitrogen (TN). TN is essentially stable at the weekly scale in forest-dominated catchments. In urban-dominated catchments, TN exhibits a modest positive bump around the flood week (on the order of ± 10 percent), followed by a slight dip and a quick return to baseline, reflecting the relatively limited nitrogen sources in urban landscapes. Agriculture-dominated catchments show much greater variability in TN, although the pattern is irregular rather than flood-driven. Large swings occur both before and after floods (± 100 percent), and confidence intervals are wide. This volatility likely reflects agricultural management dynamics—fertilizer application, irrigation cycles, manure spreading, and drainage practices, all of which can induce substantial fluctuations in nitrogen loads independently of specific flood events. This suggests the need for deeper investigation into nitrogen dynamics under compound events, including examining the drought-

to-flood sequences, which are more likely to lead to greater mobilization of contaminants (especially N and P) from agricultural fields.¹³

Other indicators (BOD, COD, Chl-a). BOD responses to floods are minimal across all land-use types. However, agricultural catchments display large week-to-week variability, with swings sometimes exceeding ± 200 percent; however, these fluctuations are not clearly synchronized with flood timing, reflecting a complex interplay between heavy rainfall events and land-management processes rather than a single flood-driven mechanism. reliable event-study estimation.¹⁴

6.5 The Strong Buffering Role of Forests

Healthy forests act as natural infrastructure within the water cycle, slowing runoff, increasing infiltration, and stabilizing river flows, helping moderate floods and strengthen infrastructure resilience. Across all major water-quality indicators—TSS, TP, TN, BOD, and COD—forest areas exhibit remarkably muted responses to floods, while non-forest areas show much greater variability and, in many cases, clear signs of disturbance. Figure 22 provides further evidence of the exceptional buffering capacity of forest-dominated catchments. These patterns reinforce the view that forests function as highly effective natural infrastructure, stabilizing hydrological and biogeochemical processes during extreme weather events. For TSS, flood events result in only minimal changes in forested catchments, with coefficients remaining close to zero throughout the event window. In contrast, non-forest areas show a pronounced post-flood spike, reflecting substantial sediment mobilization.

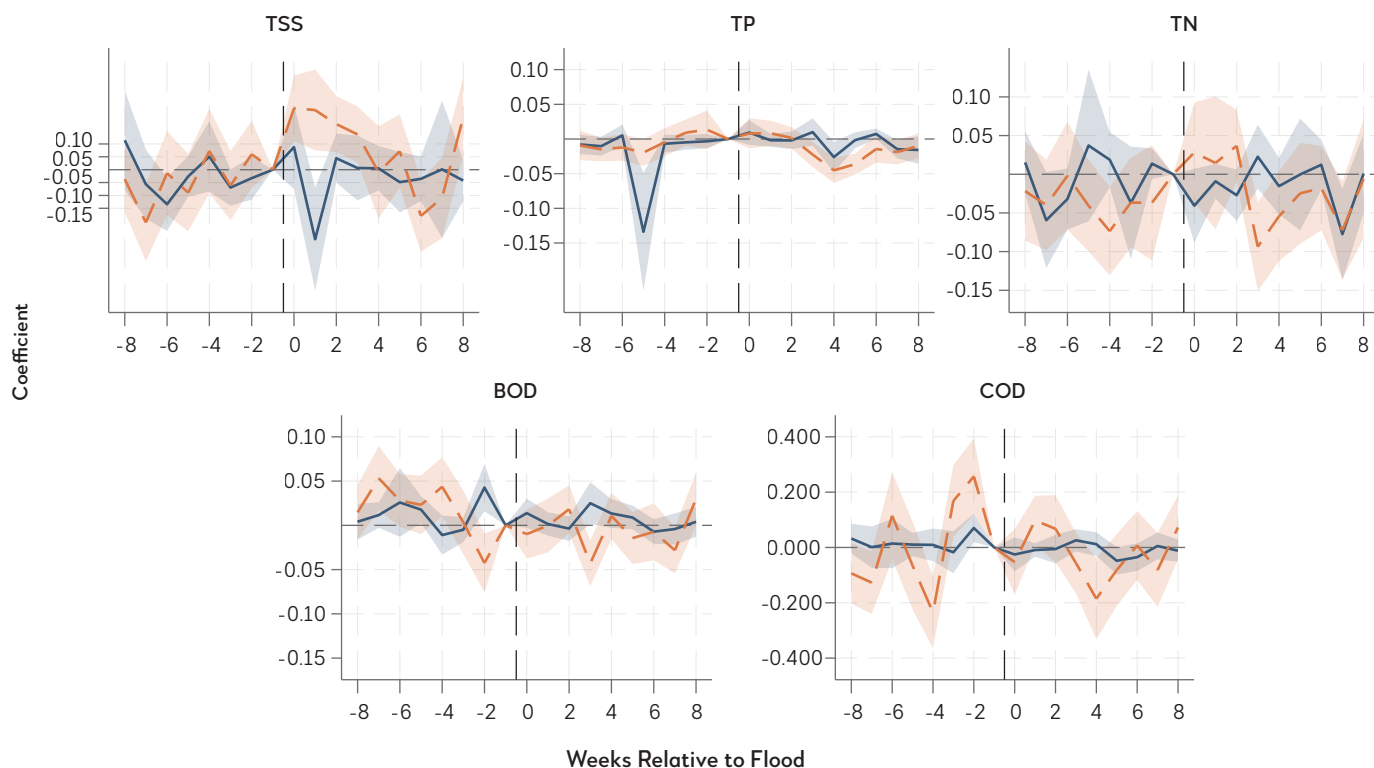
This contrast indicates that post-flood sediment surges are concentrated almost entirely in non-forest landscapes, while forested catchments substantially dampen sediment export even under high-flow conditions.

¹³ Recent study suggests that more than half of nitrogen fertilizer applied worldwide is never taken up by crops, instead leaking into water bodies and the atmosphere, imposing substantial health, ecosystem, and economic costs [Damania et al. (2025)].

¹⁴ A series of robustness checks is conducted to systematically assess the stability of the estimated flood impacts on water quality. These include additional fixed effects (country, time, station fixed effects), as well as the removal of extreme values. The resulting coefficients remain stable across these expanded specifications. Hence, there is confidence that flood pollution effects highlighted in this chapter are not driven by omitted spatial or temporal heterogeneity, nor extreme values in the sample.

Figure 22: Heterogeneous TSS Responses (Forest vs. Non-Forest)

Blue: Forest-dominated | Orange: Non-forest areas



Notes: TSS, TP, TN, BOD: unified Y-axis (-0.15 to 0.1). COD: automatic scale. Shaded areas: 95% CI. Reference: Week -1.

Source: AIIB staff estimates.

This divergence reflects fundamental differences in land cover: Forest soils are protected by deep root systems, dense understory vegetation, and the cushioning effect of canopy cover, all of which reduce raindrop impact, inhibit surface erosion, and prevent sediment from being transported downslope. Non-forest areas, particularly those dominated by agriculture or mixed rural uses, lack these stabilizing features, making them more susceptible to soil disturbance and sediment pulses during intense rainfall. The buffering role of forests extends beyond sediment dynamics.

For TP and TN, forest-dominated catchments show almost no measurable deviations around the flood event, while non-forest areas display modest but clearer fluctuations. Similarly, BOD and COD remain essentially flat in forested areas throughout the event window. Non-forest catchments show higher baseline variability but no clear flood-related signal. Week-to-week COD fluctuations in non-forest areas are larger and more irregular, yet they do not systematically increase around the flood week.

Taken together, these findings demonstrate that forests substantially reduce both the magnitude and volatility of flood-induced water-quality shocks. By stabilizing soil structure, filtering runoff, promoting infiltration, and protecting riverbanks, forest ecosystems prevent short-term disturbances from translating into detectable changes in downstream water quality. Forests not only help reduce floods through their water absorption capacity but constitute a critical defense against the impact of hydrological extremes, and their conservation and restoration remain essential components of strategies to strengthen water quality under climate change. Forests are key to water quality.

6.6 Concluding Remarks

This chapter provides global-scale, event-based evidence on how floods affect river water quality across diverse landscape types. The results demonstrate that flood impacts are highly heterogeneous and strongly mediated by dominant land use within each catchment.

Forested catchments consistently emerge as the most stable and flood-resilient landscapes. This remarkable stability reflects the strong buffering capacity of intact forest systems: Root networks stabilize soils, canopy cover reduces raindrop impact and overland flow, and forest soils efficiently retain and transform nutrients. As a result, forests show negligible responses to flooding and function as natural regulators that shield river systems from flood-driven water-quality disturbances.

Agricultural landscapes see very different dynamics. They are the land-use type that generates the most pronounced flood-related disruptions, although impacts vary by pollutant. Sediment concentrations show extremely large and immediate post-flood spikes—often several hundred percent above baseline—reflecting the hydrological vulnerability of exposed soils, ploughed fields, and drainage channels. For phosphorus and nitrogen, agricultural catchments display pronounced volatility more than what can be explained by floods alone. These dynamics are negative for both human and ecological health. For example, excess phosphorus accelerates eutrophication, triggering algal blooms and hypoxia. This kills off natural life in large quantities and further compromises drinking-water safety. Nitrogen pollution poses similarly severe risks: elevated nitrate concentrations contaminate groundwater and surface water, increasing the incidence of waterborne disease and chronic health conditions.

Forested catchments are the most resistant to flood-induced water-quality deterioration, agricultural areas are the most sensitive, and urban and mixed catchments fall in between. The results carry significant implications for climate adaptation, watershed management, and land-use planning. Flood-driven pollution pulses reveal how natural and built systems jointly regulate water quality and also where vulnerabilities will intensify under climate change.

First, forest conservation and restoration should be seen as key nature-based strategies for maintaining water quality under increasingly frequent and intense floods. Investments in forest buffers, riparian vegetation, and watershed protection zones can substantially reduce sediment and nutrient pollution during storm events.

Second, because agricultural areas are the primary source of flood-driven water-quality deterioration, agricultural policy and extension services must focus on improving soil conservation, erosion control, and nutrient management practices. Sustainable land management programs, including potential payments for ecosystem services and capacity-building, help reduce the impacts of agriculture on water quality. Subsidies should be repurposed to promote sustainable agricultural practices (e.g., the EU's Common Agricultural Policy eco-schemes). Farmers act as stewards of the landscape; their actions can play a key role in reducing post-flood runoff and nutrient delivery.

Third, water-quality monitoring and early-warning systems should explicitly incorporate land-use heterogeneity, recognizing that agricultural regions require more intensive monitoring, particularly during drought–flood sequences that may amplify nutrient mobilization.

The results highlight the need to invest across the water system to protect upstream watersheds, strengthen midstream storage and drainage, and upgrade downstream wastewater and stormwater systems. Such investments clarify where natural infrastructure provides high-value buffering and where engineered systems are essential.

This chapter demonstrates that nature-based solutions, especially forest conservation, play an essential role in strengthening watershed resilience, while targeted improvements in agricultural management are indispensable for mitigating flood-driven water-quality shocks. These findings point to several actionable priorities:

- Protect and restore forests as natural water-quality infrastructure.
- Strengthen agricultural runoff and nutrient management to reduce pollutant mobilization during extreme events.
- Upgrade drainage, stormwater, and wastewater systems to enhance the capacity of built infrastructure under climate extremes.
- Develop early warning systems, integrating hydrological data, monitoring networks, and upstream land-use information to support real-time forecasting.
- Advance governance reforms and integrated watershed–land-use planning to align actions across sectors and jurisdictions.

- Deploy financing instruments that value and leverage nature as infrastructure, enabling scalable investment in ecosystem-based resilience. Together, these insights provide a foundation for designing integrated climate-resilient water-resource and land-use policies across both developed and developing regions.

Box D: Economic Impact of Floods and Subsequent Recovery. Evidence from South India^a

The southern Indian state of Kerala faced extreme rainfall and flooding affecting most districts between June and August 2018. These were the state's worst floods since 1924 and among India's most severe floods since 1900, claiming 504 lives and directly affecting 23 million people. The Government of India classified it as a "calamity of severe nature," recognizing the extensive loss of life, widespread displacement, and large-scale damage to housing and infrastructure. Two government orders showed that ₹3.3 billion (first tranche) of immediate assistance was provided in August, which covered crop losses, ex gratia payments, food, clothing, and housing repairs across all 14 districts. The second, issued in December 2018, earmarked ₹900 million specifically for repairing flood-damaged houses.

Household expenditure and income. Compared to neighboring unaffected states, household expenditure in Kerala declined by 13 percent during June to August. Expenditure remained significantly below pre-flood levels through December. The decline was driven mainly by non-essential spending, while food expenditure recovered more quickly after the disaster. In contrast, household income displayed a V-shaped pattern: income fell during June–August by around seven percent but rebounded strongly from September onward, exceeding income levels in unaffected districts by the end of 2018. This recovery was driven almost entirely by wage income, whereas non-wage income (e.g., income from business profits, dividends, interest, rent, and incomes from all other non-labor sources, as well as government and private transfers) remained persistently lower.

Credit and borrowing behavior. Aggregate bank credit increased significantly in the post-flood quarter, with no corresponding rise in deposits. Households had to borrow not for consumption but for housing repairs and medical expenses. Borrowing for education was unaffected. These patterns align with disaster-related repair needs and liquidity constraints.

Role of reconstruction and relief in recovery. A hypothesized channel is that the recovery was driven by a reconstruction boom in the months following the disaster. Higher aggregate demand stemming from reconstruction may increase wages if labor supply does not respond sufficiently. This is very likely in Kerala because of its heavy dependence on migrant labor, particularly for manual jobs.

Indeed, indirect evidence points to post-disaster reconstruction as a key driver of the recovery. Districts receiving higher per-capita government relief experienced faster household income growth. Analytical results indicate that higher relief allocations were significantly associated with additional income growth between August and December 2018. This highlights the need for post-disaster investments not only to rebuild but also to help boost incomes—a relevant lesson for other developing economies affected by such natural disasters.

Further analysis indicates that poorer households experienced larger income losses during the flood months but benefited disproportionately during the recovery. Income gains in the post-flood period were strongest at the lower end of the income distribution, consistent with increased demand for low-skill labor during reconstruction. In addition, analysis of demand for work under a major rural employment guarantee scheme indicates a tightening of labor market in Kerala in the months following the flood.

In summary, there were major short-run economic disruptions during the flood period, followed by a rapid but uneven recovery led by wage growth, credit expansion, and reconstruction activity. The floods underscore the importance of climate-resilient infrastructure in developing economies or regions with high flood risks. The recovery experience also underscores the importance of timely relief and reconstruction in shaping post-disaster economic outcomes, holding important lessons for policy makers as well as MDBs and IFIs.

^a This is based on the findings in Beyer et al. (2025).



CHAPTER 7

PROTECTING WETLANDS

HOW EFFECTIVE ARE INTERNATIONAL ENVIRONMENTAL AGREEMENTS?

HIGHLIGHTS

- Wetlands are critical components of natural water infrastructure with varied hydrological functions, including regulating flows, buffering floods, recharging groundwater, and sustaining biodiversity, yet they continue to experience degradation.
- Although a Ramsar designation is intended to protect these essential water ecosystems, its overall causal impact on wetland health is limited, indicating that international commitments in the absence of local institutional capacity are insufficient to protect these hydrological assets.
- Ramsar sites perform better in countries with strong environmental governance and water-management institutions, and in smaller wetlands that are easier to monitor and manage, while larger wetlands often yield weaker outcomes due to greater management complexity and underinvestment.
- Strengthening wetland protection requires pairing international agreements with local capacity, coordinated water and environmental planning, stronger governance, and integrating wetlands with grey infrastructure to enhance hydrological resilience and support long-term conservation.

7.1 Introduction

Managing multiple pressures on socio-ecological systems represents one of the most pressing policy challenges of our time. Wetlands are important socio-ecological systems whose degradation can weaken Earth's natural water infrastructure and undermine global water security. International

environmental agreements (IEAs), a key component within global environmental and water governance, have been widely adopted to promote and coordinate global and regional responses to such challenges. However, quantitative evidence regarding the effectiveness of these IEAs is scant and has so far yielded little evidence in support of IEAs solving these global environmental challenges

[Hoffman et al. (2022); Ringquist and Kostadinova (2005); Kellenberg and Levinson (2014)].

The effectiveness of IEAs has been difficult to evaluate because empirical economic research has faced obstacles in credibly identifying their impacts. Credible counterfactuals rarely exist, making it difficult to determine how countries would have acted in the absence of an agreement. In this chapter, these challenges are overcome by examining the impacts of the Ramsar Convention on Wetlands of International Importance (Ramsar Convention) on wetland health and resources. This IEA, focused on the protection and sustainable use of global wetlands, allows countries to designate wetland sites as ‘Ramsar’ sites, with countries agreeing to protect these wetland habitats, including their vegetation, water resources, and biodiversity.

The Convention was adopted in 1971. As of March 26, 2025, there were 2,535 Wetlands of International Importance (Ramsar Sites) on the Ramsar List.

This spatial and temporal variation in the adoption of a Ramsar designation combined with geospatial data on environmental outcomes such as water, vegetation, and biodiversity allows us to construct a quasi-experimental research design that causally estimates the impact of a Ramsar designation on wetland health.

While several studies document the loss and degradation of wetland-related environmental outcomes in local and global studies [Xiong et al. (2023)], there is a lack of causal evidence regarding the effectiveness of designating a wetland site to the list of Ramsar sites in terms of improving wetland health or slowing the rate of wetland loss. Therefore, this chapter contributes to the literature by exploiting spatial-temporal variation in the adoption of a Ramsar designation globally, using a difference-in-difference framework to empirically test the effectiveness of such a designation in improving environmental outcomes in wetland areas. In addition, the chapter tests the heterogeneity in the impacts of a Ramsar designation across country-level environmental performance, water governance metrics and country income, to illustrate the importance of local environmental governance and financial capacities in mediating the effectiveness of Ramsar in conserving and restoring wetland health.

7.2 The Ramsar Convention and the Protection of Global Wetlands

Wetlands serve as biodiversity hotspots, play a critical role in carbon sequestration, and are essential to regulating the global water cycle. In some circumstances, they also buffer communities from floods, droughts, and storm surges [Bullock and Acreman (2003); Rojas et al. (2022)]. Global Wetland Outlook (2025) estimates that remaining wetlands provide benefits of up to Int\$39 trillion per year. However, wetlands are rapidly degrading, with an estimated 411 million hectares—about 22 percent of global wetlands—lost since 1970. This is likely because (a) wetlands produce goods and services that are rivalrous but non-excludable, and (b) managing these common-pool resources is challenging as it requires consistency and coordination across multiple policy areas (agriculture, environment, water, etc.) and along multiple layers of governance (sub-national, national, and international).

The Ramsar Convention works as a multilateral environmental governance tool aimed at conserving and sustainably using wetlands by promoting their wise use, protecting listed sites of global importance, and fostering international cooperation to safeguard these ecosystems and their biodiversity. Under the Convention, each country (*Contracting Party*) must designate at least one wetland in its territory for inclusion on the List of Wetlands of International Importance and ensure its effective conservation and management in accordance with Article 2 of the Convention. Parties are further obligated to promote the “wise use” of all wetlands within their jurisdiction, defined as maintaining their ecological character through ecosystem-based approaches integrated into national planning, legislation, public education, and management systems.

Additionally, under Article 4, parties must establish nature reserves in wetlands (including non-Ramsar sites), support training in wetland research and management, and encourage scientific exchange and monitoring.

Finally, they are required under Article 5 to cooperate internationally, especially concerning transboundary wetlands, shared water systems or migratory species, facilitating coordinated policies

and consultations with other Contracting Parties.¹⁵ In addition, by conserving wetlands, promoting transboundary cooperation, and integrating wetland protection into national policy, Ramsar provides the ecological foundation on which the objectives of other IEAs (e.g., the Convention on International Trade in Endangered Species and the Convention on Biological Diversity) can succeed.

7.3 Trends in Wetland Health in Ramsar Sites

Since its adoption, global participation in the Ramsar Convention has expanded rapidly. Between 1995 and 2018, more than 1,500 wetland sites were designated as Ramsar sites worldwide, representing some of the most ecologically valuable wetland ecosystems across all continents.¹⁶ Despite these conservation commitments, evidence suggests that the ecological condition of many Ramsar wetlands has continued to deteriorate over the past three decades.

Using global land cover data from the European Space Agency's Climate Change Initiative, the analysis documents a significant transformation in land and water use within Ramsar-designated sites.¹⁷ Over the period of 1995–2018, Ramsar wetlands lost nearly 2,000 square kilometers of permanent water, approximately 12,000 square kilometers of vegetation cover, and more than 10,000 square kilometers of forested areas. In parallel, anthropogenic land use expanded substantially: Urban settlement increased by about 2,000 square kilometers, while agricultural land expanded by nearly 20,000 square kilometers, which is 10 times the size of urban expansion. These changes illustrate the ongoing pressures from urbanization,

agriculture, and other anthropogenic activities even within areas designated for protection. These trends highlight a significant loss of natural water infrastructure over time, leading to a decline in the ability of wetlands to regulate floods, purify water, and support complex food webs critical to the environment and biodiversity.

Biodiversity outcomes also reflect ecological decline. Using the Biodiversity Intactness Index (BII) compiled by the Natural History Museum, Ramsar sites have experienced a measurable reduction in biodiversity over the 2001–2015 period.¹⁸ The BII, which tracks the average abundance of native species relative to pre-industrial baselines, shows a consistent downward trend, indicating that the ecological integrity of these wetlands continues to erode despite formal designation under the Convention.

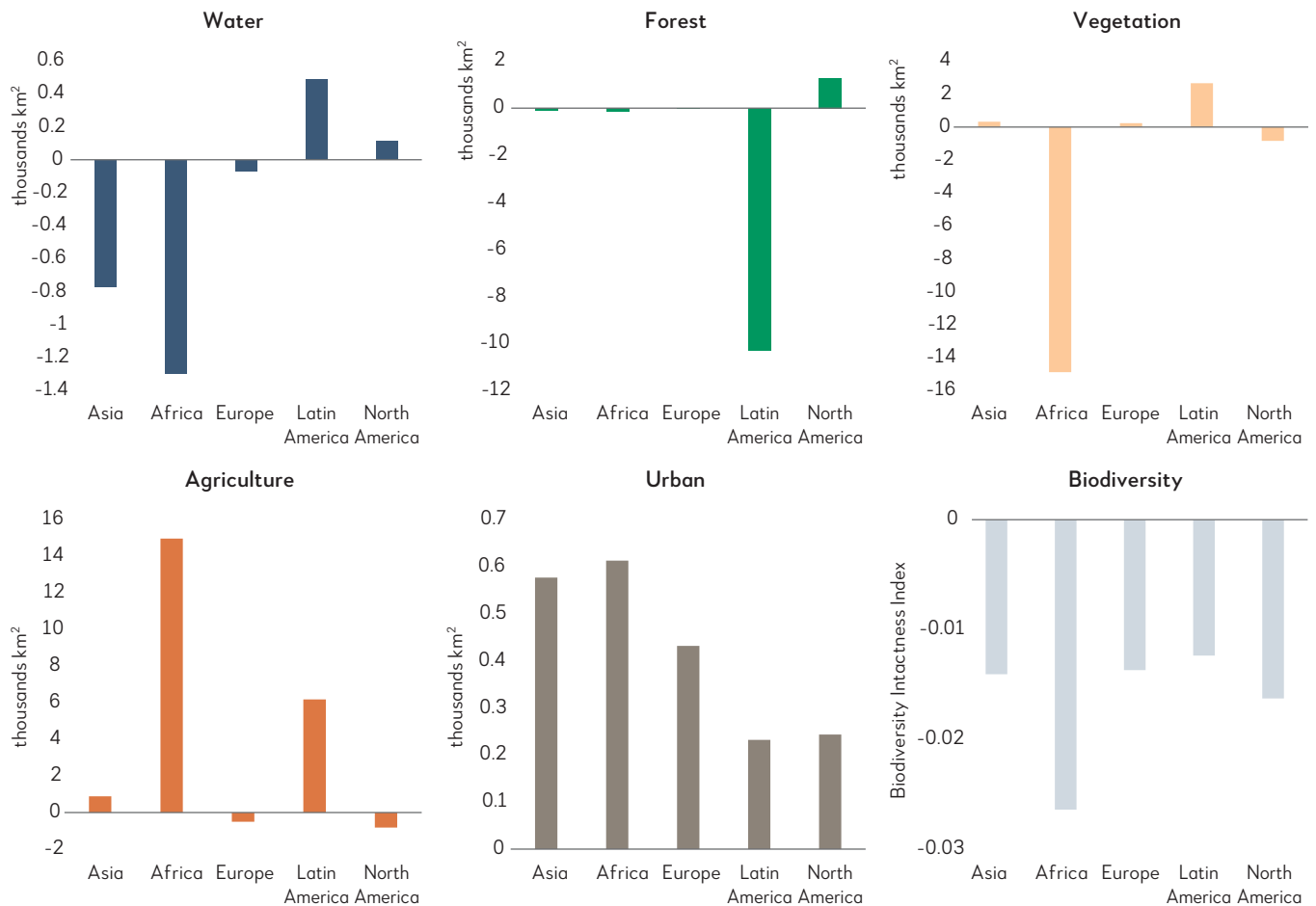
The decline in wetland health, however, is not uniform across regions (Figure 23). Africa and Asia account for the largest surface water losses, about 1,300 square kilometers and 800 square kilometers, respectively. Latin America shows the most dramatic forest loss, with approximately 10,000 square kilometers of forest converted largely into agriculture (5,000 square kilometers) and urban areas (200 square kilometers). Africa experienced the most significant vegetation decline, losing nearly 15,000 square kilometers, primarily to cropland conversion. Urban expansion has been a common driver of ecological loss across all regions, with particularly large increases in Africa and Asia (around 600 square kilometers each). These regional differences highlight both the shared global pressures facing wetlands and the importance of local land-use dynamics in shaping ecological outcomes.

¹⁵ Despite these obligations, the Ramsar Convention lacks a formal enforcement mechanism. Reporting is voluntary, key terms such as “wise use” remain undefined, and Article 2.5 allows states to delete or restrict site boundaries based on “urgent national interest,” creating potential loopholes that may weaken conservation commitments. Further and more detailed convention text and all its articles can be found here: https://www.ramsar.org/sites/default/files/documents/library/current_convention_text_e.pdf

¹⁶ Ramsar sites are estimated by creating a circle matching the reported area of each designated wetland. After excluding overlapping areas and ocean sites, the total number of unique Ramsar wetlands designated since 1995 is approximately 1,500.

¹⁷ “Water” refers to permanent water bodies; “vegetation” includes shrub, herbaceous cover, seasonally flooded areas, shrubland, and grassland; “forest” includes tree cover and mosaic tree cover.

¹⁸ The Biodiversity Intactness Index (BII) is developed by the Natural History Museum and measures the average abundance of native species in a given region relative to pre-human-impact levels. The index is available annually from 2001 to 2015.

Figure 23: Land Cover Changes in Ramsar Sites Across Regions (1995–2018)

Notes: km² = square kilometers.

Source: AIIB staff estimates.

7.4 Impacts of the Ramsar Designation on Wetland Health

The analysis finds that a Ramsar designation has had limited and often statistically insignificant effects on improving overall wetland health, with baseline models showing only minor positive impacts on forest cover and negative impacts on water extent (Table 4).¹⁹ However, these average effects mask substantial heterogeneity: Countries with stronger institutional capacity, measured by higher

Environmental Performance Index (EPI) scores and better water governance, experience measurable improvements in Wetland Health Index (WHI) and BII, while those with weaker governance and lower EPI scores often see deterioration, largely due to agricultural pressures and enforcement gaps.²⁰ Similarly, higher-income countries leverage Ramsar status more effectively than low-income countries, where financial and institutional constraints limit conservation outcomes.

¹⁹ However, after accounting for heterogeneous treatment effects due to staggered treatment timing and the potential selection into treatment due to voluntary adoption of a Ramsar designation through the 'doubly-robust' Callaway and Sant'Anna (2021), these effects become statistically insignificant.

²⁰ The WHI is a summary measure, estimated using a standardized inverse-covariance weighted approach following Anderson (2008). Water extent, forest, and vegetation cover are weighted positively, while urban and agricultural expansion are weighted negatively (Refer to Appendix 3 for detailed discussion on methodology).

Table 4: Ramsar Treatment Effects

Average treatment effect on the treated	Wetland Index	Water	Vegetation	Forest	Agriculture	Urban	Biodiversity
Two-way Fixed Effect	0.001 (0.004)	-0.0135** (0.007)	-0.007 (0.009)	0.0145* (0.008)	-0.002 (0.008)	0.010 (0.017)	-0.0008** (0.000)
Callaway and Sant'Anna	-0.009 (0.005)	-0.021 (0.015)	-0.011 (0.011)	0.011 (0.023)	0.030 (0.021)	-0.055 (0.043)	-0.0022** (0.001)
Covariates	Yes	Yes	Yes	Yes	Yes	Yes	Yes
FE: Wetland	Yes	Yes	Yes	Yes	Yes	Yes	Yes
FE: Wetland Type	Yes	Yes	Yes	Yes	Yes	Yes	Yes
FE: Country	Yes	Yes	Yes	Yes	Yes	Yes	Yes
FE: Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Clustered standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Source: AIIB staff estimates.

Wetland size also matters: Smaller wetlands tend to benefit more from designation because they are easier to monitor and manage, whereas larger wetlands face enforcement challenges and competing land uses. These findings underscore that Ramsar's effectiveness depends heavily on local governance, institutional capacity, and resource availability.

Since IEAs are implemented through local environmental protection and financial institutions, it is important to examine the impacts of IEA as moderated by these local institutional capacities. In the next section, interactions with institutional effectiveness measures, income levels, and wetland size are presented to shed light on the role of institutions and local capacity in moderating the effectiveness of a Ramsar designation.

Heterogeneity by Environmental Performance and Water Governance Measures

The overall weak effects of a Ramsar designation mask important variation across countries with different institutional capacities. One way to unpack this is to examine how impacts vary across broader measures of environmental performance. Using the EPI, which provides a gauge of how countries are

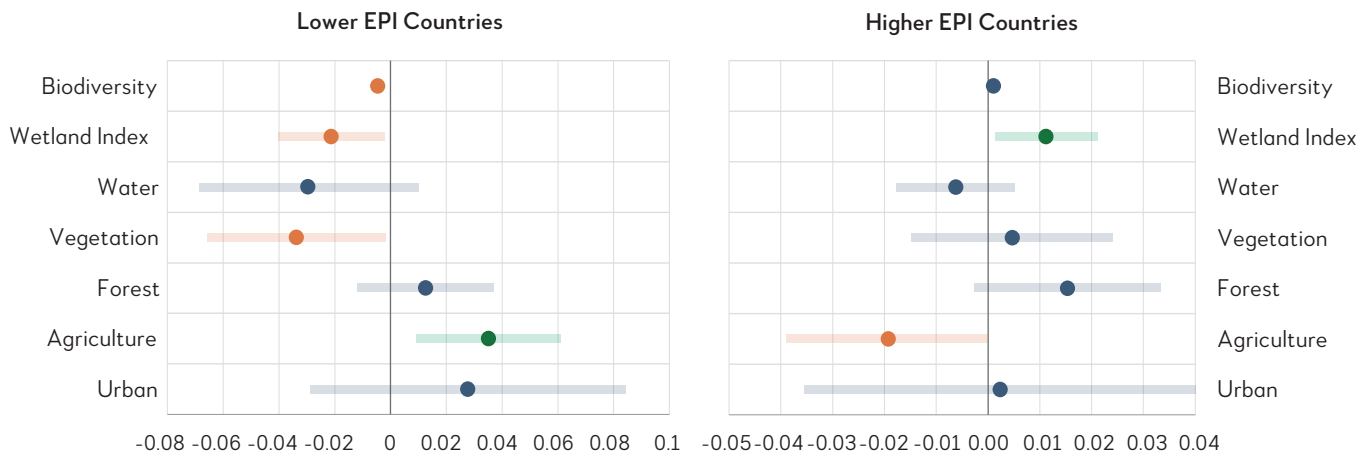
performing in terms of improving environmental health and ecological vitality [Block et al. (2024)], a clear divergence emerges.

In countries that rank above the global median in EPI score, a Ramsar designation is associated with measurable improvements in wetland health, while countries below the median perform poorly after a Ramsar designation (Figure 24).²¹ Much of this deterioration in below-median EPI countries is linked to agricultural pressures, given that these countries may lack the regulatory environment and capacity to enforce conservation, or the ability to provide alternative livelihoods. As EPI scores are closely correlated with GDP per capita, these findings likely reflect inadequate institutional and financial capacity to improve the ecological character of Ramsar sites.

The positive impacts on WHI and BII in above-median EPI countries highlight the importance of local institutional quality in implementing conservation and restoration activities. Indeed, better vertical and horizontal integration of governance structures combined with institutional effectiveness is critical to improving overall environmental outcomes as well as implementation of international treaties [Ostrom (2007); Young (2011)].

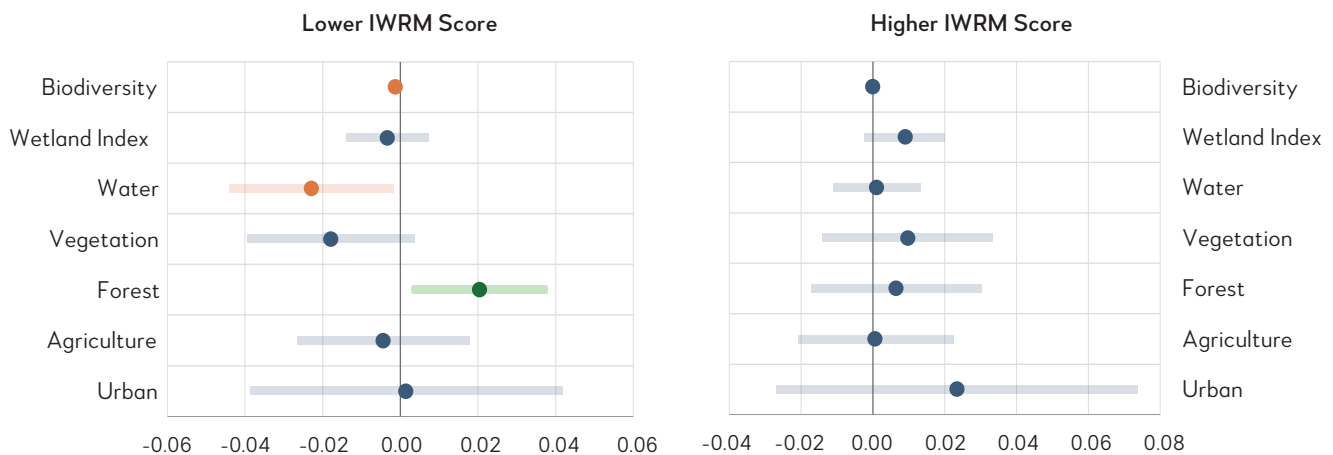
²¹ The WHI is composed of variables measured in square kilometers. Thus, even small changes in the index represent significant changes in terms of square kilometers, reflecting economically and environmentally important impacts.

Figure 24: Ramsar Treatment Effects by EPI Level



Source: AIIB staff estimates.

Figure 25: Ramsar Treatment Effects by IWRM Score



Source: AIIB staff estimates.

A similar pattern can also be observed when considering the quality of water governance structures within each country. Drawing on the Integrated Water Resources Management (IWRM) data portal, which tracks the implementation of SDG 6.5.1, the analysis indicates that a Ramsar designation performs poorly in countries with weak water governance.²² The effect of a Ramsar designation is negative in terms of water extent for countries that rank below-median on the IWRM index, while there is little to no impact for countries that rank above-median on this scale (Figure 25).

Much like the previous observations, this negative impact of Ramsar likely indicates inadequate progress toward IWRM in below-median IWRM countries. These results again reiterate the importance of improvements in local institutions and governance structures in maintaining and restoring complex socio-ecological systems (see Box E: Lessons from Sri Lanka and Pakistan on Wetlands Management and Restoration for examples of infrastructure and governance priorities identified for specific wetlands in Pakistan and Sri Lanka).

²² SDG 6.5.1 tracks the degree of integrated IWRM implementation, by assessing the four key components: enabling environment, institutions and participation, management instruments, and financing.

Heterogeneity by National Income Levels

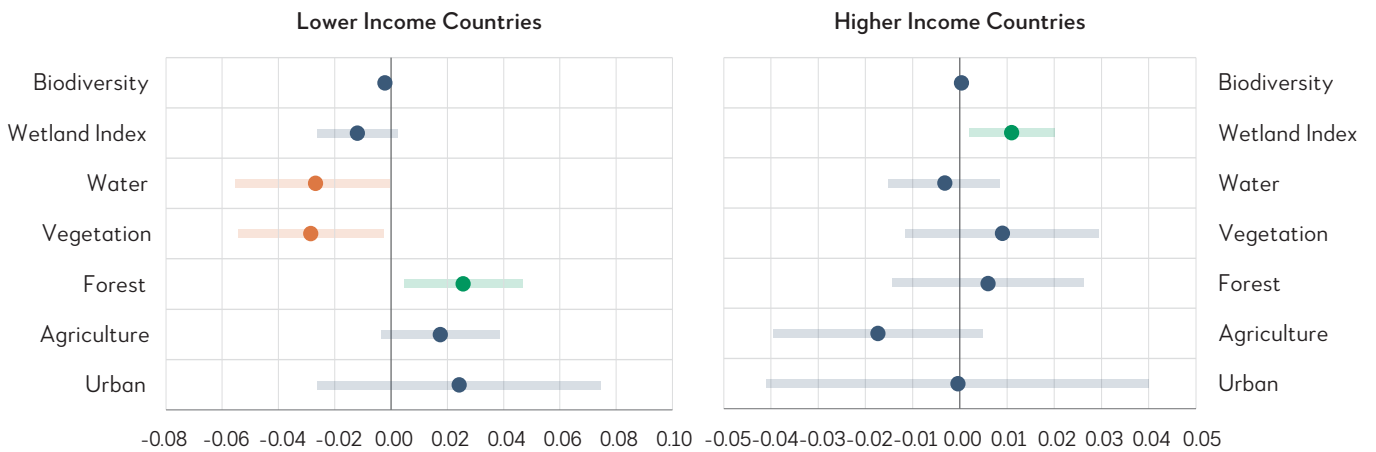
Institutional capacity is often closely intertwined with financial resources, and the variation in Ramsar effects across income levels illustrates this point clearly (Figure 26). In low- and lower-middle-income countries, limited funding and a lack of facilities, such as payments for ecosystem services (PES), may hinder the ability to leverage Ramsar status for ecological conservation, eco-tourism, or sustainable development projects. In contrast, higher-income countries typically have stronger governance systems, better enforcement capacity, and access to financing for conservation-compatible development, allowing them to offset costs and capture benefits (e.g., tourism, ecosystem services) from a Ramsar designation. This results

in a negative net impact in poorer countries but a neutral (positive in some instances) impact in wealthier ones.

Heterogeneity by Size

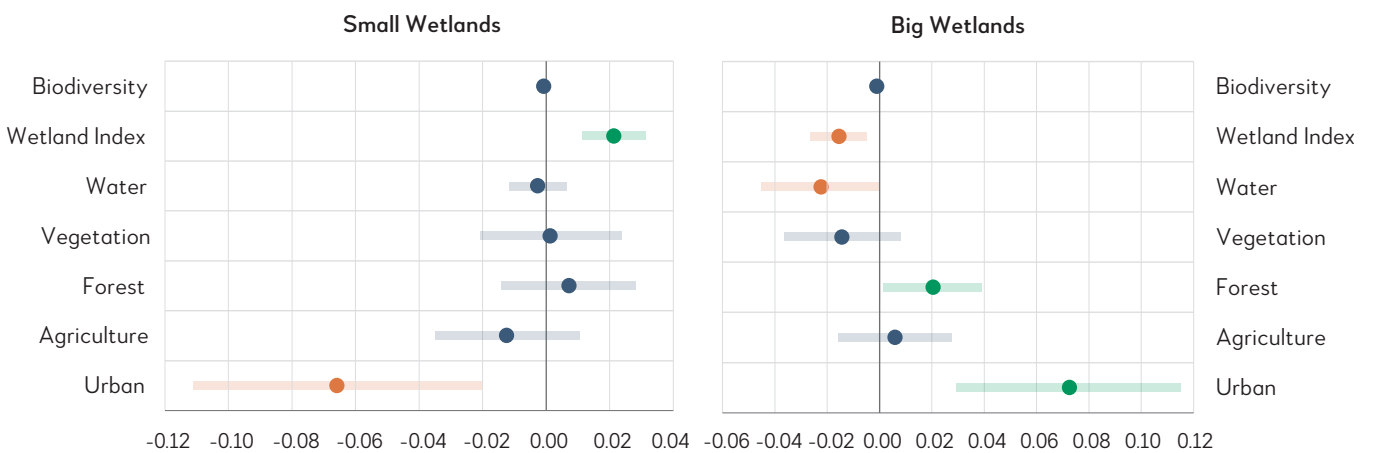
The size of designated wetlands also plays a role in shaping Ramsar outcomes. Smaller wetlands tend to perform better under a Ramsar designation than larger ones (Figure 27). Smaller wetlands may experience stronger protection effects after a Ramsar designation, as they are generally easier to monitor, enforce, and manage within existing institutional and financial constraints. A limited size may also mean fewer competing land uses, reducing the likelihood of conflicts and compliance

Figure 26: Ramsar Treatment Effects by Countries' Income Level



Source: AIB staff estimates.

Figure 27: Ramsar Treatment Effects by Wetland Size



Source: AIB staff estimates.

challenges. In addition, smaller wetlands typically require lower restoration and maintenance costs, making it more feasible for governments or local communities to implement conservation measures effectively.

Conversely, larger wetlands often span multiple jurisdictions, involve diverse user groups, and face higher opportunity costs from restricted economic activities, which can dilute enforcement and lead to partial or symbolic implementation of Ramsar commitments. As a result, a designation translates into more tangible conservation outcomes for smaller wetlands compared to their larger counterparts.

7.5 Concluding Remarks

The results of this study reveal that the effectiveness of a Ramsar designation is mediated by local institutional quality and financial capacity, suggesting that IEAs, in the absence of improvements in local conservation mechanisms and institutions, are insufficient to guarantee conservation outcomes. Several policy implications follow.

First, IEAs should be complemented by efforts that strengthen local institutions and regulatory mechanisms. This includes investments in governance transparency, enforcement mechanisms, and local capacity for adaptive

management, as weak institutions undermine the ability to translate international commitments into on-the-ground action.

Second, financial support mechanisms are essential to offset the opportunity costs of wetland protection in resource-constrained settings. Instruments such as dedicated conservation funds, payment for ecosystem services, blended finance arrangements, and Public-Private Partnerships for Nature can help ensure that conservation actions do not impose disproportionate economic burdens on vulnerable communities.^{23,24}

Finally, policy design should emphasize alignment across multi-level governance, ensuring that global objectives are embedded in national legislation and operationalized through local institutions. Legal recognition of community-based organizations, clear delineation of responsibilities, and participatory decision-making processes can enhance compliance and legitimacy. Emerging innovations in domestic water law offer complementary pathways for strengthening national implementation (see Box E). Taken together, these measures can transform IEAs into practical instruments for sustaining and restoring complex social-ecological systems such as wetlands.

Protecting wetlands strengthens the natural infrastructure of the water cycle and provides a cost-effective complement to engineered water management systems.

²³ The Delta Blue Carbon (DBC) project in Pakistan is one of the world's largest tidal wetland and mangrove restoration initiatives, leveraging carbon credit revenues and community stewardship to sustain long-term conservation. Further details are provided in Box F.

²⁴ For an extended discussion on Public-Private Partnerships for Nature and their application in blue carbon and ecological restoration projects, see AIIIB, EBRD, and Paulson Institute (2023).

Box E: Lessons from Sri Lanka and Pakistan on Wetlands Management and Restoration

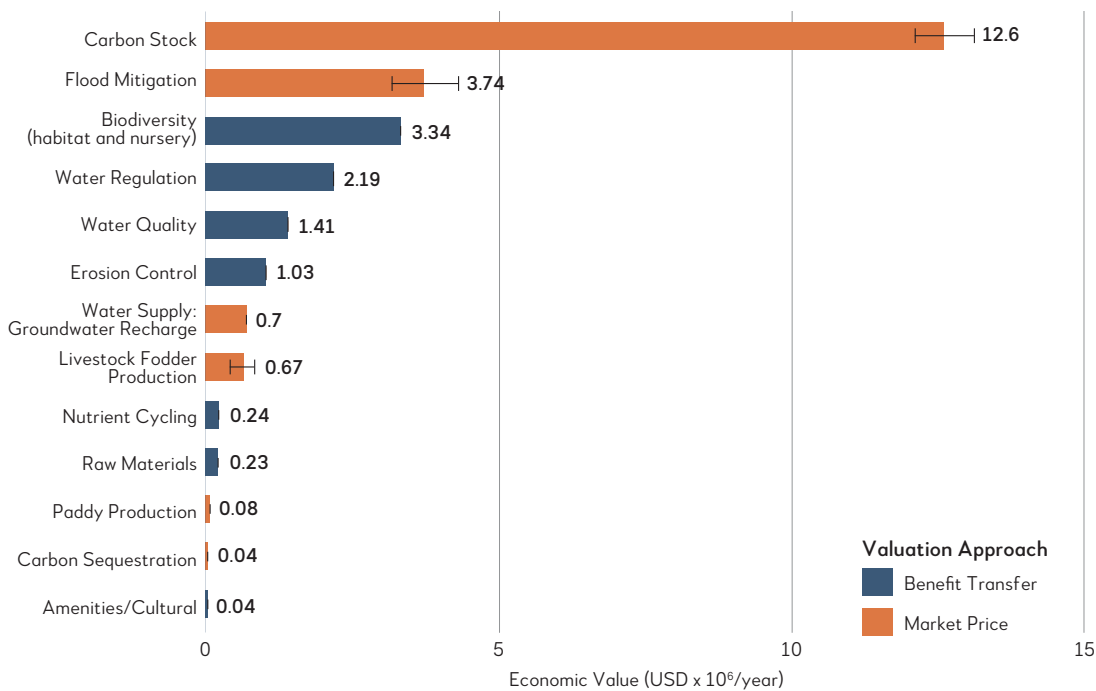
As highlighted in the chapter, a Ramsar designation alone is insufficient to safeguard wetlands, especially when land-use pressures, climate variability, and institutional fragmentation undermine long-term resilience. This box presents two contrasting but complementary examples: the peri-urban wetlands of Sri Lanka’s Kalu Oya and Mudun Ela basins, and the rain-fed Uchchali Wetlands Complex in Pakistan, which illustrate how integrated planning, green-grey infrastructure solutions, and strengthened governance can improve wetland outcomes.

Sri Lanka: Integrating Peri-Urban Wetlands into Urban Water Management

Pressures on peri-urban wetlands. The Kalu Oya and Mudun Ela basins, located in Sri Lanka’s fast-urbanizing Gampaha District, have experienced rapid landscape change. Between 1975 and 2016, they lost over 60 percent of natural vegetation cover and 10 percent of wetland extent, leaving wetlands at just 14 percent of the basin area by 2023. Population growth, limited natural drainage, and insufficient engineered drainage have heightened flood risks. Recognizing these pressures, a major flood mitigation master plan developed by the Japan International Cooperation Agency (JICA) proposes a hybrid approach that combines canal rehabilitation, diversions, pumping stations, and nature-based solutions such as wetland restorations and wetland parks [JICA (2023)].

Valuing ecosystem services for informed planning. To inform integrated basin planning, the International Water Management Institute assessed 13 ecosystem services across provisioning, regulating, supporting, and cultural categories in the two basins [Wickramaratne et al. (2026)]. The combined value is estimated at USD25-28 million, with major contributions from carbon storage, flood mitigation, and biodiversity (Figure E1). Excluding one-time carbon stock, the annual flow value is roughly USD13-14 million, which is conservative relative to global wetland valuation benchmarks due to data limitations on some services such as thermal regulation. The valuation highlights that wetland restoration can be a cost-effective flood management strategy, alongside grey infrastructure (e.g., flood protection dikes) and soft options including early warning systems and social protection.⁹

Figure E1: Economic Values for Selected Ecosystem Services in Kalu Oya and Mudun Ela Basins



Source: AIIB staff estimates.

Box E *continued*

Policy implications. Three priorities emerge:

1. Integrate natural capital into development planning to balance land conversion pressures with hydrological and economic benefits.
2. Pair wetland restoration with targeted grey investments to enhance climate-resilient flood management.
3. Strengthen cross-agency coordination so that wetland functions are consistently reflected in land-use, drainage, and environmental decision-making.

Pakistan: Infrastructure and Governance Priorities for the Restoration of the Ucchali Wetlands Complex

Ecological significance and pressures. The Ucchali Wetlands Complex, consisting of three lakes in Pakistan's semi-arid Salt Range, depends entirely on rainfall. These lakes regulate the micro-climate, stabilize soils, recharge groundwater, and support migratory bird species and local livelihoods. Over recent decades, however, ecological health has declined due to irregular rainfall, pollution from inadequate waste management, extraction of wetland vegetation for fuelwood, agricultural runoff, and limited hydrological and ecological monitoring [Ali et al. (2022)].

Policy takeaways. Key priorities include:

1. Investing in water and waste infrastructure, such as buffer zones, sediment traps, decentralized wastewater treatment, and improved municipal solid waste systems.
2. Promoting clean energy options such as solar cookstoves and biogas units to reduce dependence on wetland vegetation and improve household energy security.
3. Enhancing community stewardship and monitoring through participatory management committees and digital platforms that track water quality and biodiversity.

Conclusion: Cross-country insights

Case studies from Sri Lanka and Pakistan illustrate how different wetland types require tailored interventions but share common strategic needs. These include integrated planning that recognizes wetlands as core components of natural water infrastructure, blended green and grey solutions that enhance hydrological resilience, stronger governance arrangements across institutions and communities, and targeted investments in monitoring, clean technologies, and water and waste management systems. These examples demonstrate that effective wetland management depends not only on protection but also on embedding wetlands within broader hydrological and development planning frameworks.

^o The 2025 floods that impacted Pakistan and Sri Lanka also emphasized the need to invest in flood resilience through investments in integrated nature-based and grey infrastructure solutions.

Box F: Blue Carbon Project in Pakistan

Over the past six years, the Delta Blue Carbon (DBC) project has resulted in the planting of tens of millions of mangrove seedlings on the south-east coast of the province of Sindh, restoring more than 75,000 hectares of degraded mangrove forests and tidal wetlands. Over six decades, DBC is projected to sequester between 140 and 200 million tons of CO₂ while generating high-quality carbon credits under Verra's Verified Carbon Standard and Climate, Community & Biodiversity Standards.^a In the first tranche, which happened in 2025, DBC sold about three million carbon credits, generating a revenue of USD40 million.^b

Financing Model. The project is a public-private partnership between Indus Delta Capital and the Government of Sindh. The local government provides long-term land leases and plays a crucial role in the legitimacy and sustainability of the project. The private partner provides upfront capital, scientific monitoring, and access to voluntary carbon markets, as DBC's financing model is anchored in carbon-credit revenues from these markets. The project monetizes its climate benefits by issuing credits for verified CO₂ removals, which are purchased by global corporations and traders, providing long-term financial sustainability. The public-private partnership approach aligns with global trends in blue carbon finance, which emphasize policy support, the development of Monitoring, Reporting and Verification (MRV) systems, and incentives for private sector participation.

Infrastructure Requirements for Sustaining DBC. The project is located in a region with high rates of poverty. Mangroves are used for fuelwood, fishing, and grazing. To incentivize conservation among the local community, DBC's success depends on engagement and ownership. The project has created over 21,000 jobs in mangrove planting, monitoring, and eco-tourism, while promoting Mangrove Stewardship Agreements that empower locals as custodians of restored lands. Investments extend to health care, education, clean water systems (reverse osmosis plants), and microfinance initiatives to build the project's credibility in the local community.^c Further infrastructure improvements include nurseries for mangrove seedlings and digital MRV platforms for transparent carbon accounting.^d These interventions address poverty and reduce reliance on fuelwood, fostering social resilience and inclusion in coastal villages.

Challenges Related to Restoration

Despite its scale, DBC faces many challenges common to blue carbon projects:

- (a) Upstream water scarcity and salinity intrusion threaten mangrove survival. Ensuring minimum water flows for ecological purposes remains a challenge in this context.
- (b) High transaction costs for carbon certification and MRV systems limit scalability. However, the deployment of digital MRV systems (including drone-based LiDAR and multispectral imaging) in the project has allowed for high-quality monitoring and verification of carbon credits.
- (c) Climate variability (cyclones, sea-level rise) adds uncertainty to restoration outcomes.

Addressing these challenges requires integrated policy frameworks, sustained financing, and adaptive management strategies that combine ecological science with community-based governance.

^a Delta Blue Carbon – Mangrove Restoration In Sindh – Delta Blue Carbon – Mangrove Restoration In Sindh

^b <https://www.dawn.com/news/1926851>

^c Market-based solutions for sustainable development: Lessons from the Delta Blue Carbon project in Pakistan | International Growth Centre

^d Delta Blue Carbon Project, Sindh - Carbon Market Institute



CHAPTER 8

INVESTING UPSTREAM FOR DOWNSTREAM RELIABILITY

HYDROPOWER BENEFITS OF ECOLOGICAL RESTORATION

HIGHLIGHTS

- Upstream vegetation restoration improves hydropower performance. A one-unit increase in upstream leaf area index (LAI) raises hydropower capacity factors by around 15 percent, mainly by stabilizing flows.
- Benefits are strongest for small and run-of-river plants and in humid regions. These systems are especially sensitive to flow timing, making them high-return locations for watershed restoration.
- The findings help clarify the economic value of upstream ecosystem services. A more accurate valuation provides a stronger analytical basis for expanding Payments for Ecosystem Services (PES) schemes and for mobilizing private capital for nature conservation.
- Integrating nature infrastructure into hydropower planning strengthens climate resilience and lowers long-term operational risk. Restoration upstream complements grey infrastructure, creating more reliable generation and expanding investment opportunities for governments and multilateral development banks (MDBs).

8.1 Introduction

The complexity of water management stems in part from the deeply interconnected nature of water systems, which generate externalities that cross geographic and administrative boundaries. Among these dynamics, upstream-downstream interactions are particularly critical. The condition of upstream

ecosystems shapes how water moves through a landscape, including runoff generation, sediment transport, groundwater recharge, and flow timing. These processes are fundamental components of the hydrological cycle and directly influence the performance, reliability, and long-term sustainability of downstream infrastructure.

As ecosystem degradation accelerates, from deforestation and wetland loss to soil erosion and watershed fragmentation, many countries are experiencing more volatile runoff patterns, rising sediment loads, and declining natural water-storage capacity. These shifts undermine the reliability of water infrastructure and heighten exposure to droughts and floods. Against this backdrop, the role of ecological restoration in sustaining hydrological functions is receiving increasing attention. Global initiatives such as the Bonn Challenge and AFR100 are expanding rapidly, offering opportunities to reverse local degradation, though hydrological outcomes vary widely depending on climate, species composition, and management practices.

Hydropower is one of the clearest examples of infrastructure that depends closely on upstream ecosystem conditions. It remains central to delivering affordable and clean energy worldwide, with global capacity reaching 1,425 GW by the end of 2024—14.7 percent of total installed capacity and 32 percent of renewable capacity [IRENA (2025)]. Hydropower depends on the stability of the water cycle. River flows, sediment transport, and seasonal storage patterns all reflect upstream ecosystem conditions and climate dynamics. Yet hydropower systems face mounting pressures from climate change, land-use shifts, and environmental degradation.

Ecological restoration—through afforestation, grassland rehabilitation, and soil and water conservation measures—has emerged as a promising strategy to address these challenges. Large-scale efforts such as China's restoration programs in the Yellow River Basin illustrate this potential. A recent *Nature Communications* study showed that ecological restoration in the Yellow River Basin reduced sediment inflow to the downstream hydropower plant Xiaolangdi and extended its sediment storage life by nearly a decade. Although lower runoff led to a modest 6.9 percent decrease in average annual generation, the extended operational life resulted in a 57.3 percent increase in cumulative hydropower output (equivalent to an extra 100 billion kWh) before the reservoir's sediment storage capacity is exhausted [Wu et al. (2025)].

These insights add to a growing body of literature linking upstream vegetation change to downstream hydrological and hydropower outcomes. However, most existing work is modelling-based (using hydrological simulations) or confined to basin-level case studies [Shafeeque et al. (2022); Guo et al. (2023); Araujo and Hector (2024); Damania et al. (2025)]. A broader empirical assessment across diverse geographic and climatic contexts remains limited.

This chapter contributes to the literature by examining how upstream vegetation influences downstream hydropower performance using a multi-country panel dataset. The study also quantifies the causal effect of upstream vegetation change across different hydropower types, plant sizes, and aridity types, providing a more nuanced understanding of where ecosystem restoration can deliver the largest benefits for hydropower sustainability.

8.2 Empirical Results

The empirical results reveal several clear policy-relevant messages. First, upstream vegetation restoration could enhance the operational efficiency of downstream hydropower plants, largely by regulating flow and stabilizing runoff. Second, these benefits are not evenly distributed: The gains are strongest for smaller and run-of-river plants and are concentrated in humid regions where vegetation tends to enhance flow regulation rather than reduce water yield.

The study focuses on the United States, Australia, and Argentina due to the high quality and availability of plant-level power generation data. A panel dataset is compiled, tracking plant-level operational data, including net electricity generation and capacity factors for around 900 hydropower plants, as well as their upstream vegetation changes and other climatic factors from 2005 to 2020, using remote-sensing and modeled data sources. Capacity factor, a measurement of electricity generation efficiency, is used as the main outcome variable. It is defined as the ratio of actual electricity produced to the theoretical maximum output, calculated as installed capacity multiplied by operational time. A detailed description of the data and methodology is provided in Appendix 4.

Using a fixed effects regression model that controls for time-invariant plant and country characteristics, common time shocks, and time-varying factors such as precipitation and temperature, the analysis shows that lagged upstream LAI, a measure of vegetation density, has a significant positive impact on the downstream hydropower capacity factor. The LAI is lagged to account for the delayed impact of vegetation changes.

On average, a one-unit increase in LAI is associated with a 0.061 increase in the capacity factor, or roughly a 15 percent efficiency improvement relative to the sample average. To contextualize the magnitude, the average LAI in the sample is 1.8; thus, a one-unit increase represents a sizable change. For comparison, China’s Grain to Green Program has generated LAI gains of 0.2-0.6 across the Loess Plateau over a decade, with some local peaks reaching around 1 [Cao et al. (2019)]. Applied to the downstream Xiaolangdi hydropower plant, a 0.2 increase in the LAI across the Loess Plateau would raise its capacity factor by about 0.01, equivalent to roughly 158 GWh of additional electricity annually.²⁵ This could supply the annual electricity needs of roughly 40,000-50,000 households in China.²⁶ While the effect of land restoration on plant performance may appear modest in the short term, its cumulative impact becomes substantial over multi-decade operating horizons and at large installed capacities.

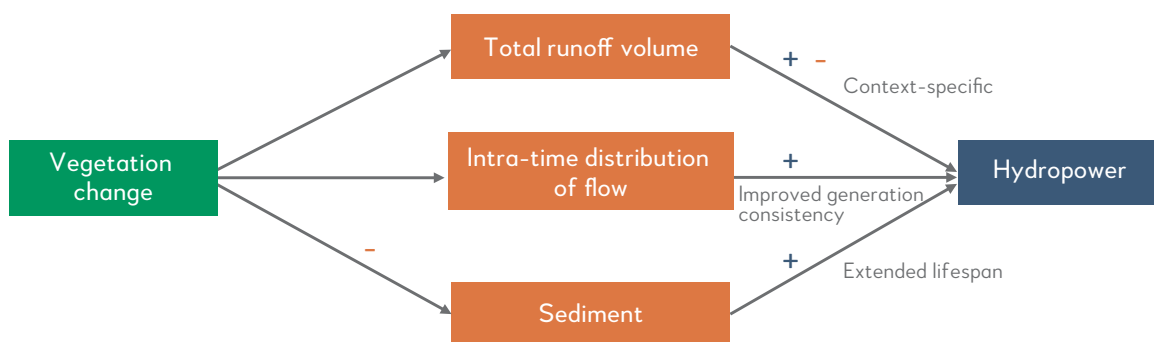
Understanding this positive relationship requires further examination of the hydrological pathways through which upstream vegetation influences

downstream generation. The literature highlights three main mechanisms:

- Total annual streamflow. Vegetation influences rainfall infiltration, evapotranspiration, and river runoff. Its impact on total annual streamflow is context-dependent: It may reduce total runoff due to higher evapotranspiration, particularly in arid and semi-arid regions [Zhang and Wei (2021)].
- Intra-time distribution of flow. Increased vegetation generally enhances infiltration, which can reduce peak flows and increase base flow, smoothing seasonal variability, and potentially improving generation consistency [Pizarro et al. (2022)].
- Sediment yield reduction. Vegetation also stabilizes soil, reducing erosion and sediment transport. Lower sediment loads will extend reservoir lifespans and reduce turbine abrasion, directly benefiting hydropower operations. [Creed and van Noordwijk (2018)].

To examine these mechanisms, annual upstream runoff and peak-season sediment concentration are introduced as mediators.²⁷ When runoff is added, the LAI coefficient remains positive and significant. When sediment is included, the LAI coefficient increases to 0.18. However, because sediment data are available for only about 20 percent of plants, it is difficult to determine whether this increase reflects the role of sediment control or simply sample composition.

Figure 28: Three Mechanisms of How Vegetation Changes Affect Hydropower Output



Source: AIIB staff estimates.

²⁵ The installed capacity of Xiaolangdi Hydropower is 1800MW, and its maximum output is 157,68 GWh per year, a 0.01 increase in capacity factor means an extra 157.6 GWh generation.

²⁶ This number assumes that a Chinese household consumes 3,000-4,000 kWh per year on average.

²⁷ Due to data availability issues, only sediment concentrations at peak months are included.

Table 5: Empirical Results

	(1) Baseline	(2) Baseline + Runoff	(3) Baseline + Runoff + Peak sediment
Lag LAI	0.061*** (0.016)	0.061*** (0.016)	0.183*** (0.044)
Installed capacity	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Temperature	-0.027*** (0.003)	-0.027*** (0.003)	-0.028*** (0.006)
Precipitation	0.231*** (0.010)	0.215*** (0.012)	0.116*** (0.034)
Total runoff		0.028** (0.014)	0.277*** (0.050)
Peak month sediment concentration			-0.026 (0.016)
Constant	0.389***	0.387***	0.386***
Observations	16613	16613	3945
Number of plants	911	911	291
Time-period	2005-2024	2005-2024	2005-2020

Notes: All regressions are carried out with country, plant and year fixed effects. Standard errors in parentheses, clustered at river level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Source: AIB staff estimates.

After controlling both runoff and sediment, the LAI coefficient remains significantly positive, while sediment is negative but not statistically significant. This implies that the efficiency gains are likely driven more by improved flow stability than by changes in total runoff or sediment alone.

As a robustness check, standard errors were clustered at the river-basin level to account for spatial correlation among plants within the same basin. Although this adjustment increased the standard errors, the coefficient for lagged LAI remained positive and significant, further supporting the robustness of the findings. While this helps mitigate interdependence across plants, a more rigorous approach, such as a spatially adjusted regression model, would be needed to fully capture potential spatial dependencies. Therefore, the results should be interpreted as robust but with some caution regarding strong causal claims.

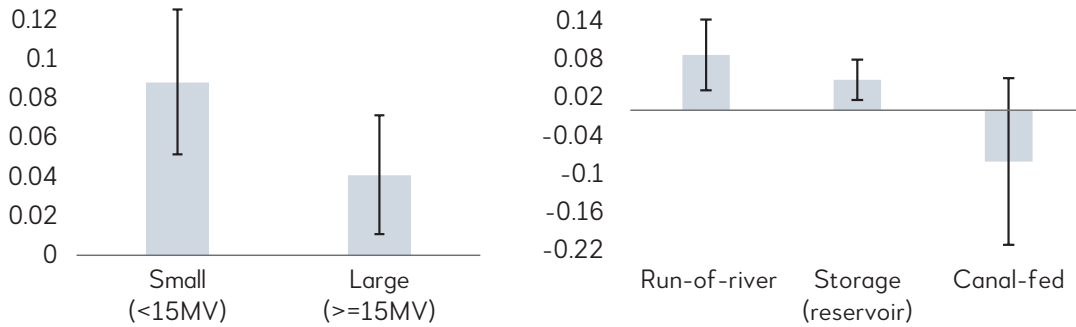
Because the fixed effects model assumes a homogeneous vegetation effect across all plants, a simplification unlikely to hold in practice, interaction terms are introduced to capture how

the impacts vary by plant size, plant type, and aridity type.

By plant size, the result shows that the positive association between upstream vegetation and hydropower performance is stronger for smaller plants (installed capacity below 15 MW), which accounts for 47 percent of plants in the sample. Smaller plants typically operate with limited storage and minimal sediment-management infrastructure. As a result, they benefit more directly when upstream vegetation reduces erosion, stabilizes runoff, and limits sediment inflow.

Similarly, plant type also matters for this relationship. The positive effect of upstream vegetation is the largest for run-of-river plants, followed by storage plants, and statistically insignificant for canal-fed plants. Run-of-river plants rely almost entirely on natural river flow, making them highly sensitive to fluctuations in runoff volume and flow timing. Thus, they respond most strongly to changes in upstream vegetation. Storage plants have reservoirs that buffer some of this variability, moderating the effect. Canal plants receive regulated flows

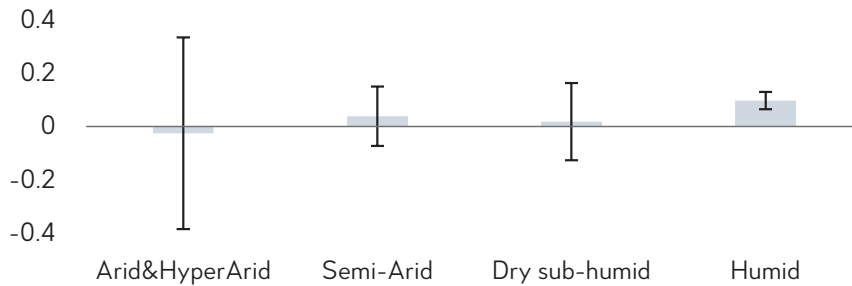
Figure 29: Heterogeneous Impact by Plant Size (Left) and Plant Type (Right)



Notes: Run-of-river hydropower plants utilize the natural flow of rivers and elevation decrease to generate electricity with little or no water storage [Galletti et al. (2021)]. Storage hydropower uses large reservoirs that allow them to generate electricity during periods of dry conditions and high energy demand [Hunt et al. (2018); Hunt et al. (2020)]. Canal-fed plants are hydropower facilities located on man-made canals or aqueducts.

Source: AIIIB staff estimates.

Figure 30: Heterogeneous Impact by Aridity Type



Source: AIIIB staff estimates.

through engineered conveyance systems, so upstream vegetation has little direct influence on their performance.

As summarized in the systematic review by Zhang and Wei (2021), the hydrological consequences of vegetation cover change were determined by watershed properties, climate (precipitation or potential evaporation), and their interactions. Thus, the analysis further explored how the impact differs across aridity type. The results show that the positive association between upstream vegetation (lagged LAI) and hydropower capacity factor is concentrated in humid regions.²⁸

This pattern aligns with the broader hydrology literature, in which afforestation in arid and semiarid areas is more likely to result in water-yield loss due

to evapotranspiration, whereas in humid regions, improvements in flow regulation and reductions in sediment delivery may outweigh the impact on water yield [Zhang et al. (2017)].

8.3 Policy Implications

The study provides robust evidence that upstream vegetation enhances downstream hydropower performance. These results highlight that ecological conditions in the watershed are not merely environmental considerations: They form an integral part of hydropower system efficiency and long-term reliability. This creates clear policy and investment opportunities. Restoring and maintaining upstream ecosystems can complement conventional infrastructure, reduce operational

²⁸ The aridity type is determined based on aridity index, defined as the ratio of precipitation to potential evapotranspiration (P/PET). Humid regions are defined areas with an aridity index greater than 0.65, following the UNEP definition.

risks, and strengthen generation stability. Based on these insights, the following section outlines two key directions for leveraging these benefits.

Promoting an Integrated Approach that Combines Traditional Infrastructure with Nature-Based Solutions (NbS)

The results highlighted the complementarity between green and grey infrastructure in the water sector context. As shown in the earlier analysis, one key channel through which upstream afforestation enhances the capacity factor of hydropower plants is the reduction of sedimentation.

Effective sediment management is critical not only for hydropower operations but also for other water-related infrastructures such as multipurpose dams that provide flood control, irrigation, and water supply. This underscores ample potential for MDBs and other financiers to integrate NbS in the future design of water projects.

Despite these opportunities, challenges remain in scaling this approach. First, evidence on the effectiveness and cost-efficiency of NbS remains limited compared with conventional engineering

solutions. As a result, NbS are often perceived as an experimental or untested approach, with most applications remaining at pilot scale—largely driven by donor-supported technical assistance rather than domestic demand. In the water sector particularly, the lack of large-scale, high-profile success stories constrains its visibility and limits the establishment of technical standards and design benchmarks for wider adoption.

Additionally, there is also a strong institutional preference for grey infrastructure, which often remains the default choice even when NbS could deliver more cost-effective outcomes [AIIB (2025)]. Afforestation, for example, is sometimes perceived as spatially inefficient due to its land requirements. However, while it lacks spatial compactness, it may compensate for life-cycle cost efficiency. NbS typically requires lower capital investment and operating and maintenance costs, making it particularly attractive in low-land-value areas—for instance, for erosion control in upstream catchments or flood protection in agricultural landscapes. While the research provides evidence on potential benefits of using NbS (afforestation) in water-related projects, it is important to further strengthen the evidence base on its performance and cost-effectiveness through systematic monitoring, evaluation, and impact studies.

Box G: AIIB's Approach to the Water-Nature Nexus

At the policy level, AIIB's Water Strategy identifies three key investment priorities—water services, resource management, and resilience enhancement—guided by four overarching principles. Among these principles, one emphasizes the adoption of innovative technologies, encompassing not only green technologies but also NbS. In practice, many of AIIB's completed and pipeline projects demonstrate its integrated approach of combining traditional infrastructure with nature-based measures to deliver co-benefits for water security, climate resilience, and biodiversity conservation. These examples are discussed in more detail below.

Enhancing Dam Resilience and Ecosystem Restoration in Indonesia

AIIB's Dam Operational Improvement and Safety Project II (DOISP2) (2017–2023), co-financed with the World Bank and the Government of Indonesia, exemplifies this approach. The project aimed to strengthen the operational efficiency of dams that serve as buffers against floods and key sources of water supply.

A major challenge identified was sedimentation, caused by years of inadequate reservoir sludge management and intensified upstream erosion due to vegetation loss. DOISP2 combines engineering measures—such as dredging and structural rehabilitation—with ecosystem restoration to address sediment accumulation and its impacts.

continued on next page

Box G *continued*

To reduce future sediment transfer, DOISP2 supported catchment revegetation, restoring over 760 hectares of degraded areas. Local communities were central to this process through a dedicated community participation component. In Aceh Province, for instance, the Water Catchment Forum worked closely with the local community to identify suitable planting sites on private land to complement work on public land and facilitated community input on species selection. Indigenous fruit-bearing trees such as jamblang, rambutan, durian, and jackfruit were chosen for their ecological and economic benefits. Long-term maintenance was formalized through a Memorandum of Understanding between the Water Catchment Forum and River Basin Organizations, representing the Indonesian Ministry of Public Works as the executing agency for DOISP2, ensuring continued co-management beyond the project's completion.

Expanding NbS Investments for Flood Resilience

AIIB is drawing on this experience to expand investments that leverage flood-regulating and erosion-reducing ecosystem services. This vision is reflected in the 2025-2029 Multiyear Rolling Pipeline for Indonesia, jointly endorsed by AIIB and the Government of Indonesia. Among its priorities is improving flood resilience across Indonesia's small islands and along the northern coast of Java (Pantura Jawa), a key economic and population hub generating over 20 percent of national GDP.

Rising flood risks from climate change, rapid urbanization, and lagging protective infrastructure have prompted AIIB to explore integrated NbS and engineering approaches. Planned interventions could include mangrove restoration and expansion to control coastal abrasion and mitigate storm surges, coupled with seawalls and dikes in urban areas to be selected based on feasibility studies. These measures aim to balance ecological restoration, climate resilience, and infrastructure protection, while supporting local livelihoods and biodiversity.

Integrating Ecosystem Restoration into Irrigation and Water Security Projects

AIIB is also investing in project preparation to scale up NbS within irrigation and flood management. Through its Project Preparation Special Fund (PPSF), AIIB has allocated USD4.95 million (2024-present) to the Country Climate-Resilient Irrigation and Water, Drought, and Flood Mitigation Project.

In Cambodia, the PPSF supports feasibility studies for the potential rehabilitation of the Trapaeng Thmor Reservoir in Banteay Meanchey Province, which irrigates about 50,000 hectares and plays a central role in national food security. The reservoir is also of ecological importance, with its hydrological connection to the Ang Trapeang Thmor Protected Landscape influencing groundwater conditions and the habitat of vulnerable and critically endangered bird species, including the Sarus Crane and the White-shouldered Ibis. AIIB investments are exploring measures to address sedimentation, reduce upstream erosion, and improve irrigation efficiency, thereby helping restore reservoir capacity and enhance ecological conditions in the Protected Landscape. PPSF financing will also support feasibility studies that consider nature-based solutions for flood and drought management, continuing its role in enabling strategic upstream analysis in Cambodia's water-nature nexus.

Encouraging the Private Sector's Participation in the Water-Nature Nexus Through Payments for Ecosystem Services (PES)

At the global level, investments in NbS and ecosystem restoration for water security have grown significantly over the past decade, reaching an estimated USD49 billion in 2023—twice the amount recorded in 2013. However, this growth remains largely driven by public expenditure, which accounts for roughly 97 percent of total investment, while private-sector participation remains limited

[TNC (2025)]. This imbalance underscores an urgent need to develop mechanisms that can better leverage the private sector's financing in the water and nature nexus.

One promising solution is through PES or PES-like schemes, which can help mobilize sustainable resources from water users. PES is not a new concept and has been extensively discussed and implemented over the past two decades. As defined by Wunder (2005), it is "a voluntary transaction where a well-defined environmental service is being bought by a buyer from a provider if and only if the provider secures service provision." In essence, PES

provides a market-based mechanism to incentivize ecosystem stewardship by aligning economic interests between beneficiaries and providers of ecosystem services. Linking to the results of this study, one potential application is for hydropower companies to allocate part of their revenue to compensate upstream communities for adopting land-use practices or implementing ecosystem restoration that reduces sedimentation.

Viet Nam's Payment for Forest Environmental Services (PFES) provides a pioneering example of such a mechanism. Enacted through Government Decree No. 99/2010, PFES requires downstream users of watershed services—including hydropower plants—to make payments to provincial Forest Protection and Development Funds. These funds are then used to compensate local households and communities for forest protection activities that support watershed health. By 2024, PFES revenues

had reached approximately VND3.7 trillion (about USD104 million), supporting job creation and livelihood improvement for around 25 million people living near forest areas [Nguyet (2025)]. Viet Nam is one of the few countries where PES has evolved into a national policy. A detailed discussion of this case is provided in Box H: Payment for Watershed Services.

The research findings help provide a more accurate value to the ecosystem services provided by upstream vegetation, offering a strong analytical foundation for scaling up similar PES schemes. The heterogeneous impact analysis also suggests that upstream reforestation and ecological restoration should be prioritized for smaller and run-of-river plants, as well as for those located in humid regions, where the performance gains from improved flow regulation and sediment control are greatest.

Box H: Payment for Watershed Services

Given the unique advantages of PES in addressing externalities, it has been widely applied globally in water-related contexts, including wetland restoration and watershed management. Recent reviews show that water-related PES schemes are the most widespread globally. Among more than 550 PES programs identified worldwide, 387 focuses on watersheds [Salzman et al. (2018)]. This subset, known as Payments for Watershed Services (PWS), typically operates through the following mechanism: Upstream service providers conserve or restore ecosystems and are compensated by downstream water users or by a third party, such as the government, often through intermediaries like water funds or NGOs.

Based on a review of PWS globally, several classic cases are selected, and their key elements and features are summarized in the following table. As demonstrated in the cases below, PWS can be used in many contexts, such as enhancing water quality, reducing sedimentation, and securing flows along the watersheds.

Following Wunder's definition, PES mechanisms can be categorized based on who ultimately pays for the services: public (government-financed), private (user-financed), or hybrid. A textbook example of a private PES scheme is the Vittel program initiated by Nestlé Waters to safeguard its water source from the adverse impacts of agricultural intensification in the catchment. Nestlé established an intermediary institution, Agrivair, to lead program design and implementation, as well as negotiations with farmers. Under this arrangement, 26 farmers voluntarily signed long-term contracts and received payments to adopt more extensive farming practices, thereby reducing nitrate contamination risks [Perrot-Maitre (2006)].

In contrast, many government-led programs—such as Viet Nam's PFES scheme—do not fully align with Wunder's strict definition, as participation is not entirely voluntary. In Viet Nam's case, the mechanism is backed by national law, and water users are required to pay fees to the national Forest Protection and Development Funds. This approach provides predictable financing for forest protection and allows social considerations to be incorporated into program design. However, as the fee levels are set by regulation, questions remain about the scheme's broader effectiveness and whether it truly reflects the underlying value of ecosystem services.

continued on next page

Box H *continued*

Table H1: PWS Selected Case and PWS-Like Scheme

Case	Provider and Action	Buyer and Intermediary	Key Feature
Vittel, France (1993)	Upstream landowners: adopting new farming practices	B: Nestlé Waters I: Agrivair	Private led and private financed
Viet Nam Payment for Forest Ecosystem Service (PFES) (2010)	Upstream landowners: forest restoration	B: Water utility, hydropower and tourism companies I: Viet Nam Forest Protection and Development Fund (VNFF)	Government led but privately financed
China's horizontal eco-compensation in Yangtze River	Upstream local government: a series of interventions to improve water quality	B: Downstream local government	Government led and government financed

Source: Perrot-Maitre (2006), World Bank (2021), and Pham et al. (2023).

While evidence on PFES's livelihood impacts remains mixed [Dang Do and NaRanong (2019); Pham et al. (2021)], findings on environmental outcomes are more encouraging. A recent study employing causal inference methods found that PFES curbs forest loss at rates comparable to or greater than those in state-managed protected areas, though significant effects emerge only after the program has been in place for more than three years [Gallemore et al. (2024)]. This suggests that even without full marketization, PES-like programs can deliver strong results in forest conservation.

Overall, while Viet Nam's PFES scheme may not meet all the strict criteria of a classic PES model, it nonetheless recognizes the value of ecosystem services and offers an innovative approach to sustaining finance while addressing environmental externalities.

8.4 Concluding Remarks

Long-term hydropower performance depends on maintaining the integrity of the upstream water cycle. This chapter shows that upstream ecosystems are integral to the hydrological cycle and materially influence downstream hydropower performance. Using plant-level data across three countries, the analysis shows that higher upstream vegetation density, as measured in LAI, significantly improves capacity factors of downstream hydropower plants, largely by enhancing flow regulation and stabilizing runoff. The benefits are especially pronounced for smaller and run-of-river plants and are concentrated in humid regions.

These insights carry wider significance for water and infrastructure policy. They demonstrate that the performance and resilience of downstream

assets depend not only on built infrastructure but also on the ecological conditions that shape the hydrological cycle upstream. Restoring watersheds and investing in upstream vegetation can reduce sediment pressures, improve the reliability of river flows, and ultimately strengthen the efficiency of hydropower systems.

Although hydropower provides a clear example, the implications extend far beyond the energy sector. Irrigation networks, water-supply reservoirs, urban flood-protection systems, and other downstream infrastructure all rely on stable, well-functioning hydrological regimes. Positioning watershed restoration as part of core infrastructure planning enables MDBs and governments to expand investment portfolios while strengthening resilience and long-term asset performance.



CHAPTER 9

WATER STRESS AND SOVEREIGN RATINGS

A CROSS-COUNTRY ANALYSIS

HIGHLIGHTS

- Water stress significantly weakens sovereign creditworthiness in developing countries. In lower-middle-income countries, a 10-percentage-point increase in water stress is estimated to result in a one-notch decline in their credit ratings. This reflects greater exposure to both water-intensive sectors and social tensions. A negative effect of a smaller magnitude is also found in upper-middle-income countries.
- Water stress continues to have a limited impact on advanced economies' credit ratings, given their economic structure and income level.
- The predicted rise in future water stress, amid ongoing climate change, underscores the urgency of supporting developing countries. Delivering sustainable water supply infrastructure as well as broader sector reforms can help address current challenges and promote longer-term fiscal stability.

9.1 How Water Stress Worsens the Macroeconomic Outlook

Water cycle stability has growing macroeconomic implications. Volatility from droughts, floods, or declining water quality can disrupt agriculture, energy, infrastructure, and fiscal stability, making water risks increasingly relevant for sovereign creditworthiness and economic planning.

Worsening climate change has led to an ever-increasingly uncertain global hydrological cycle, leaving much of our water resources at risk.

For instance, droughts and changes in evaporation can reduce upstream supply levels, which then spread downstream, causing widespread scarcity. Indeed, in their most recent World Water Development Report, the United Nations (UN) emphasizes how around half of the planet's population already experiences severe water stress at some point of the year [FAO and UN-Water (2024)].

Global water demand is expected to continue increasing through 2050, with UNESCO (2024) indicating an increase of roughly 20 to 30 percent above current levels by 2050.

The trend in temperature levels, meanwhile, will prolong droughts and lead to unstable supply, leaving a serious mismatch in water availability [Klobucista and Robinson (2023)]. The breakdown of the hydrological cycle as natural infrastructure, whose components perform the necessary water management functions, is what ultimately leads to widespread water stress.

This alarming outlook for water availability poses grave economic and social challenges for policymakers. The literature describes two main channels through which water stress can drive a broader macroeconomic downturn: a decline in economic activity and a deepening of political tensions.

The first channel pertains to the water intensity of major industries, including agriculture and manufacturing, where the lack of a key input can upend both local and global supply chains [Dolan et al. (2021); Ross et al. (2024)]. In turn, this can lead to heightened food and energy insecurity as the spillover effects spread across sectors [Hertel and Liu (2016)].

Volatility in production levels consequently drags on both immediate and longer-term output, putting strain on the economy. Indeed, estimations of the output effect from high levels of water scarcity reinforce this line of argument. Sharma and Tiwari (2023) analyzed the effects of water stress on the Gross Domestic Product (GDP) per capita growth of 16 highly stressed countries, with empirical findings indicating a negative relationship.

More broadly, Frost, Madeira and Jaramillo (2025) ran output regressions across 169 countries, concluding that a one-standard-deviation rise in water scarcity is associated with a 0.12 percent to 0.16 percent decrease in GDP growth. Narrowing the focus on the importance of major water bodies for regional economic prosperity further highlights our dependence on water. A recent report by China Water Risk (2025) explores the mounting challenges facing Asia from the drying of major river basins. In the worst-case scenario for peak flows, the total GDP of sixteen regional countries spanning Central to East Asia may contract by half. Without a secure water supply, countries struggle to produce food, generate energy, and trade. This creates a reliance on favorable climate change conditions for economic growth, risking a volatile outlook.

The second channel, political tensions, arises from increased competition over limited water resources. Social unrest often arises from frustration with public services and inequality, exacerbating political uncertainty [Gbandi (2022)]. Unequitable outcomes over water access can also lead to grievances that fuel divisions within a community, likely in areas already prone to unrest. Any volatility arising from a desire to control water supply could further dampen external investor confidence. This is not limited to a single country: The need to secure dwindling transboundary resources in water-scarce regions may cause cross-border tensions, introducing a broader geopolitical risk element to water stress and the macroeconomy [Akash, Sharif and Chowdhury (2025)].

9.2 The Growing Concern for Rating Decisions

Credit rating agencies have increasingly taken water stress into account when determining their sovereign ratings. Fitch Ratings, for example, notes the growing importance of water risks in general as a rating driver, especially on the back of climate change, while referring to the two main channels discussed above [Harb and Chen (2020)]. Additionally, spending pressures and contingent liabilities can harm public finances, creating another avenue through which creditworthiness may be negatively affected. Fitch Ratings has accordingly integrated water risks in its sovereign rating framework. Water Resources and Management is also one of the five environmental factors that are assigned an Environmental, Social, and Governance (ESG) score. This feeds into the rating by assigning a weight to a country's fiscal exposure to water scarcity.

Furthermore, Moody's Ratings and S&P Global Ratings both note that higher global temperatures will increase the need for governments to manage water stress, given its impact on creditworthiness [Moody's Investors Service (2023); S&P Global Ratings (2023)].

The increased likelihood of droughts disrupting agricultural production, supply chains, and food availability is linked to concerning projections for climate change. The response from governments to these multifaceted economic challenges has become of particular interest: The agencies have

been paying close attention to national policies on sustainable water management to assess their preparedness for the future.

9.3 Water Stress in Developing Countries

Many developing countries are in regions already grappling with intensified water stress, such as Sub-Saharan Africa and Southeast Asia [FAO and UN-Water (2024)]. Continued rapid urbanization is expected to drive local water demand amid broader population growth, placing further strain on limited availability [Klobucista and Robinson (2023)]. Simultaneously, their relatively weaker institutional capacity constrains the sustainable management of water resources, resulting in more frequent shortages as water scarcity worsens.

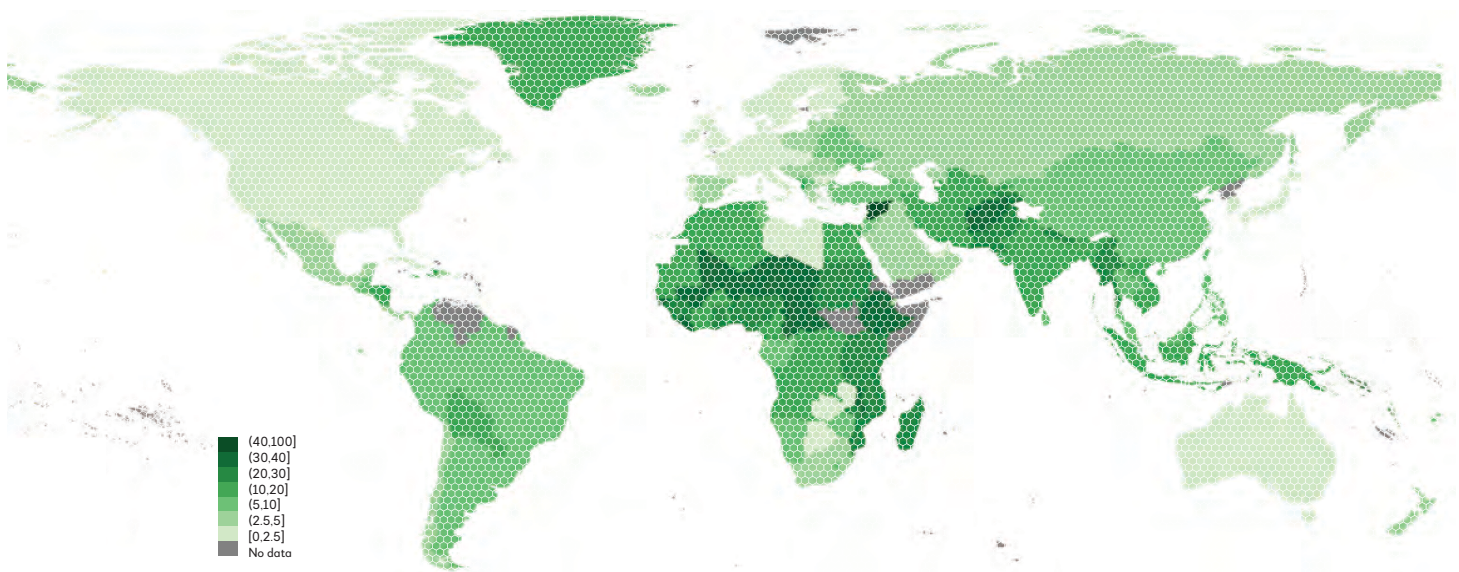
Developing economies are also more exposed to the two identified channels through which higher water stress negatively harms sovereign ratings. First, their agricultural sectors, on average, constitute a larger share of total GDP and employment than in advanced economies, with many farmers reliant on water-intensive processes such as irrigation for their livelihoods (Figure 31). The estimation of the output effect of water scarcity, particularly in lower-income

countries, further underscore their pronounced vulnerability to climate change. One such example, from the Global Commission on the Economics of Water (2024), predicts a contraction in GDP of up to 15 percent by 2050, compared to a median of eight percent for high-income countries. It again cites the broader consequences for food production and economic stability as key factors in the disparity between projections. The combination of qualitative and quantitative evidence on developing countries' exposure to water stress underscores the urgent need to prioritize climate change and water management.

Moreover, many such countries are prone to social unrest, often directed at the perceived ineffectiveness of government services due to weak institutional capacity. More common instances of volatile water, and subsequently energy and food security, will only further spur domestic tensions. Miguel et al. (2004) depict this relationship econometrically, concluding that periods of low rainfall increase the likelihood of civil unrest in Sub-Saharan Africa.

This study aims to formalize the relationship between water stress and sovereign ratings, utilizing various regression models to estimate the impact of higher stress levels on a country's credit rating.

Figure 31: Share of GDP from Agriculture by Country (2024)



Source: Our World in Data. Based on national statistical organizations and central banks, OECD national accounts, and World Bank staff estimates (2025).

9.4 Implications for Infrastructure Investment and Policy Decisions

The main findings express that while higher water stress is not associated with a meaningful decline in a country's credit rating for advanced economies, this relationship becomes decisively negative for developing economies. The effect is most pronounced for lower-middle-income countries, which is consistent with the two main channels of transmission identified by both the literature and credit agencies, namely, that developing countries have a greater economic reliance on water-intensive agricultural sectors and are more prone to political tensions exacerbated by unstable and unequal water supply [Harb and Chen (2020)].

Since the average credit rating of the lower-middle-income countries in the sample is lower, around B+/B1 compared to BB/Ba2 in upper-middle-income countries and in A/A2 high-income countries, the magnitude of the findings is of economic relevance. Importantly, the findings imply that the countries most at risk of intensified water stress affecting their credit ratings are those already facing fiscal challenges. As water stress is projected to only worsen by 2050, and with many developing countries facing extreme levels of stress, the prospect of long-term rating downgrades deeper into junk territory is a concern to both policymakers and lenders alike [Aqueduct (2025)].

The study's outcome ultimately reinforces the urgency of strengthening water infrastructure in developing countries, especially those most exposed to the effects of climate change. Such investments span the hydrological cycle. For instance, investment in sustainable infrastructure that increases water supply, such as large-scale water transfers, storage, reuse, watershed health, or desalination, may help mitigate shortages and offer long-term reliability for local communities [Ofwat (2025)].

Agricultural yields will experience less pressure while broader domestic economic activity will remain stable. Additionally, social pressures will ease as access to water improves. Strengthening both these economic and political channels can improve the country's fiscal outlook and instill confidence in its creditworthiness.

Indeed, credit rating agencies have themselves stated the importance of water supply infrastructure projects in mitigating sovereign risk. Moody's, for example, recommended in 2024 that India invest in water management for its ratings outlook, as "decreases in water supply can disrupt agricultural production and industrial operations, resulting in inflation in food prices and declines in income for affected businesses and communities, while sparking social unrest" [Reuters (2024)]. Nature-based solutions and basin resilience exemplify how green and grey infrastructure can be effectively combined to protect essential aspects of the hydrological cycle.

Alongside encouraging greater capital flows toward climate-resilient water supply infrastructure, renewed efforts to deliver broader reforms for national water sectors should also be on the agenda for developing countries. Currently, governments face a range of governance and institutional challenges, such as weak regulatory frameworks and limited capacity.

Encouraging the implementation of enforcement mechanisms for water quality, pricing, and allocation, as well as upskilling local staff to monitor ongoing reform efforts, is key to longer-term resilience [OECD (2025)]. As noted in the UN (2024) World Water Development Report, equitable arrangements can promote harmony in communities and deliver a win-win outcome across industries. Capacity development in tension-prone zones and transboundary water basins, specifically, can further strengthen the knowledge base and catalyze the adoption of new technologies for mutual benefit. Of course, improving local capabilities not only encourages sustainable water management but also creates an environment more conducive to fiscal consolidation, further strengthening the credit outlook.

Overall, these findings, as in Cevik and Jalles (2023), emphasize the need for developing countries to climate-proof their economies amid evolving risks. Water stress, as one example of climate vulnerability, is shown here to harm the macroeconomic and political outlook. Given the relatively high borrowing costs that many of these countries currently experience, policymakers should

focus on delivering structural improvements in the national water sector to attract greater investment in water supply. The total financing gap for water infrastructure is already considerable—up to some USD7 trillion globally by 2030, according to some estimates [Khemka and Sterte (2024)]. Effective allocation of resources is therefore key to ensure that the water sector, and consequently the credit outlook, of developing countries becomes more resilient.

9.5 Designing a Study to Explore Water Stress and Credit Ratings

A country-year panel dataset is initially constructed, incorporating the necessary variables for the analysis. Data on historical sovereign credit ratings, our main dependent variable, is obtained from Bloomberg. The platform offers country-year ratings data from the three main ratings agencies (Fitch Ratings, Moody's Ratings, and S&P Global Ratings), to which an ordinal value between 1 (C) and 21 (AAA/Aaa) is assigned.

Meanwhile, a measure of water stress is taken from the FAO as the independent variable of interest [FAO (2025)]. It is estimated as a percentage, specifically, freshwater withdrawal as a proportion of available freshwater resources.²⁹ Since the water stress dataset spans 2000 to 2022, the analysis is limited to this time frame. Importantly, there remains sufficient variation in country-level water stress ratios for countries over the chosen period. Appendix 5 provides the list of the countries included in the final analysis.

Conventional determinants of sovereign credit ratings are also included as control variables, following the literature [Bissoondoyal-Bheenick (2005); Cantor and Packer (1996); Monfort and Mulder (2000)]. Sourced from the International Monetary Fund (IMF), they are: real GDP, inflation, general gross government debt, current account, population, unemployment, and foreign exchange reserves [IMF (2025)]. Following Cevik and Jalles (2023), the effect of an increase in water stress on a sovereign's credit rating can therefore be estimated by the following baseline regression:

$$R_{it}^* = \beta WS_{it} + \gamma X'_{it-1} + \alpha_i + \delta_t + \varepsilon_{it}$$

where WS_{it} is the chosen indicator of water stress for country i in year t measured as a share, while R_{it}^* denotes the average credit rating across Fitch Ratings, Moody's Ratings, and S&P Global Ratings. Similar to Cevik and Jalles (2023), the chosen vector of macroeconomic control variables denoted by X'_{it-1} , is lagged by one period to mitigate any endogeneity issues. Year fixed effects δ_t and country fixed effects α_i are also included, while ε_{it} is the error term.

The initial estimation method involves running a fixed effects panel ordinary least squares (OLS) regression with a balanced panel of observations across countries and years. However, taking credit ratings as a qualitative ordinal measure suggests that the ordered response model may be more suitable for the data [Bissoondoyal-Bheenick (2005)]. An ordered probit regression is therefore the second approach taken, given its relevance to this study's sample. A Poisson pseudo-maximum likelihood (PPML) estimator, of the type proposed by Santos Silva and Tenreyro (2006), is also tested.

The three chosen econometric specifications employ different methodologies to assess the relationship between water stress and credit ratings. The baseline model above is then split into country subsamples according to the World Bank 2026 fiscal-year income classification system. This produces three additional sets of regressions which quantify the relationship for high-income, upper-middle-income, and lower-middle-income countries, respectively. The credit impact can then be compared across country groups as well as with the original all-countries estimation.

9.6 Main Findings Across Country Groups

Table 6 first provides an overview of all countries in the sample, where the effect is negligible and statistically insignificant. The interpretation of the coefficient of interest is as follows: A one percentage point increase in a country's water stress is associated with an estimated 0.0113

²⁹ Kuwait, United Arab Emirates, Saudi Arabia, and Libya are removed from the dataset given that water stress levels in these countries are at least 10 times that of average water stress in the dataset (64.3 percent). The average water stress levels between 2000 and 2022 in these countries are 2,996 percent, 1,676 percent, 916 percent, and 759.8 percent, respectively.

Table 6: Water Stress Impact on Ratings (All Countries)

	(1) OLS	(2) Ordered Probit	(3) PPML
Water Stress	-0.0113 (0.0113)	-0.00871 (0.01142)	-0.000898 (0.000884)
Macro-Financial Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Observations	1,744	1,744	1,744
Number of Countries	92	92	92

Notes: Standard errors in parentheses are clustered at the country level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: AIIB staff estimates.

Table 7: Water Stress Impact on Ratings (High-Income Countries)

	(1) OLS	(2) Ordered Probit	(3) PPML
Water Stress	0.00477 (0.00877)	0.00544 (0.01119)	0.000388 (0.00065)
Macro-Financial Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Observations	910	910	910
Number of Countries	47	47	47

Notes: Standard errors in parentheses are clustered at the country level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: AIIB staff estimates.

decline in its credit rating (on the 1–21 scale) under the OLS approach, for instance. There appears to be no clear negative link between water stress and sovereign ratings when testing the relationship for all countries at once.

Table 7, meanwhile, presents the findings for high-income countries. Unlike the initial set of results, there appears to be a positive but economically and statistically insignificant association between water stress and credit ratings. This is consistent with the fact that developed economies, on average, rely less on agricultural production and tend to experience less political instability.

Therefore, the two main channels through which higher water stress could impact credit ratings are less prevalent for high-income countries. The relatively strong macroeconomic fundamentals, including public and external finances, give further support to why advanced economies can better manage the potential fallout from water insecurity.

The findings for developing economies are presented in two tables: Table 8 for upper-middle-income countries and Table 9 for lower-middle-income countries. The findings for the former now indicate a negative link between water stress and credit ratings.

Table 8: Water Stress Impact on Ratings (Upper-Middle-Income Countries)

	(1) OLS	(2) Ordered Probit	(3) PPML
Water Stress	-0.0289 (0.0220)	-0.0367 (0.02345)	-0.00287 (0.00240)
Macro-Financial Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Observations	581	581	581
Number of Countries	31	31	31

Notes: Standard errors in parentheses are clustered at the country level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ *** $p < 0.01$

Source: AIB staff estimates.

Table 9: Water Stress Impact on Ratings (Lower-Middle-Income Countries)

	(1) OLS	(2) Ordered Probit	(3) PPML
Water Stress	-0.0861** (0.0342)	-0.0948** (0.03895)	-0.0106*** (0.0037)
Macro-Financial Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Observations	236	236	236
Number of Countries	13	13	13

Notes: Standard errors in parentheses are clustered at the country level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: AIB staff estimates.

While not statistically significant, the coefficients are of a greater magnitude than when running the models for the whole countries sample: A one percentage point increase in water stress reduces sovereign credit ratings by up to 0.037 units on a 1-21 scale. This is equivalent to a 27-percentage-point rise in water stress being associated with a one-notch downgrade in ratings.

Finally, focusing only on lower-middle-income countries, Table 9 shows a considerably larger and statistically significant relationship between water stress and sovereign ratings: A one percentage point increase in water stress is associated with a decline on the 1-21 ratings scale of a magnitude ranging between 0.011-0.095.

This result is statistically significant at the five percent level in columns (1) and (2) and at the one percent level in column (3), giving confidence to the findings despite a smaller sample size. In other words, these findings imply that as little as a 10-percentage-point increase in water stress can drive a one-notch decline in credit ratings in lower-middle-income countries.

Overall, these results confirm that water stress can negatively impact a country's creditworthiness. As expected, the magnitude of this relationship varies dramatically across income groups; in advanced countries, it is nonexistent, whereas in developing countries it is economically significant. For lower-middle-income countries, this result is not only

economically significant but also statistically significant at the five percent and one percent levels. Appendix 5 provides the details of a proxy regression on another environmental stress indicator to confirm that these findings are indeed unique to water stress.

9.7 Concluding Remarks

Intensifying levels of water stress will pose a severe challenge for developing countries, which are particularly exposed to the economic and social consequences of water scarcity. This translates into a projected decline in creditworthiness as the fiscal outlook weakens, thereby impacting sovereign ratings and, consequently, borrowing costs. In lower-middle-income countries, a one percentage point rise in water stress is associated with around a 0.1 percentage point decrease in the credit rating on the 1-21 scale. The study exemplifies the unique vulnerabilities that developing economies face from worsening climate change.

The findings emphasize the need to improve water supply infrastructure in lower-income countries to secure reliable water access, thereby easing economic and social pressures. At the same time, domestic reforms can solidify sustainable water management while catalyzing much-needed investments into critical infrastructure. Both regional and multilateral coordination would prove indispensable toward achieving shared policy objectives and streamlining financing initiatives. Future work may wish to dive deeper into the two main channels, namely economic activity and political tensions, through which water stress drives credit ratings. It may be that various sectoral compositions and institutional arrangements explain differences within developing countries, as well as between developing and advanced economies.

Strengthening water cycle resilience should therefore be understood as both an environmental priority and a macroeconomic stability strategy.

Box I: Mapping Water Stress with Population and Crop Risks

Most countries experience low to moderate water stress on a national scale [FAO and UN-Water (2024)]. However, stress often intensifies within individual river basins, where water availability is uneven and misaligned with population growth and economic activity [FAO and UN-Water (2024); Ligtvoet et al. (2018)]. Agriculture is the largest user of freshwater globally, accounting for 72 percent of total withdrawals [FAO (2025)]. These pressures will increase as population growth and climate change compound existing constraints. This box maps water stress together with population concentrations and major crop production zones, identifying regions where vulnerabilities are most likely to intensify and where water-system resilience will require targeted investment across the hydrological cycle.

Population Exposure in Water-Stressed Basins

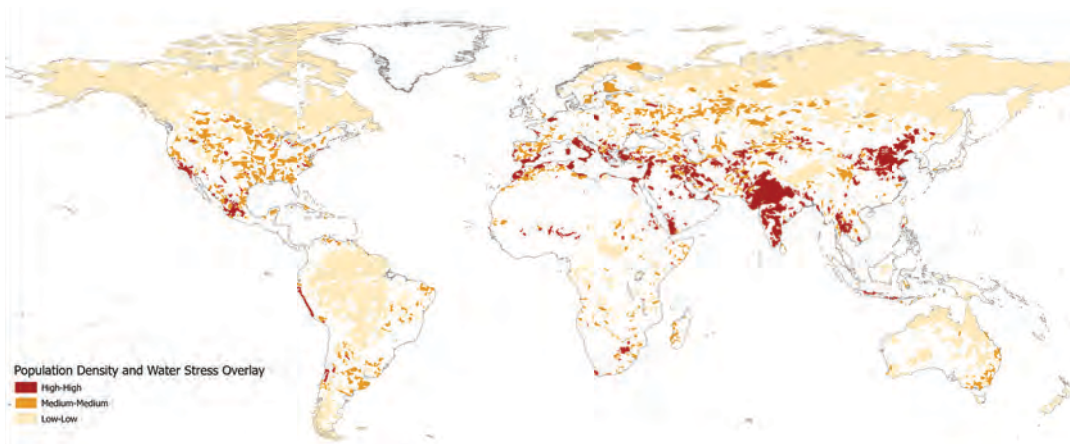
Figure I1 shows where population density and water stress intersect. Baseline water stress measures total water withdrawals relative to renewable surface and groundwater supply [Kuzma et al. (2023)]. The highest concentrations of stressed populations occur in the Middle East and North Africa and South Asia, where nearly three-quarters of the population live in basins with high population intensity and severe water stress. South Asia records over one billion people residing in constrained basins. In East Asia and the Pacific and in Europe and Central Asia, roughly one-fifth of the population lives in basins where density and stress overlap. These basins face the sharpest constraints as demand grows and rainfall variability increases, with direct implications for water-supply infrastructure, irrigation reliability, and urban resilience.

Agriculture Hotspots Under Stress

Approximately one-quarter of global cropland lies in regions where water availability is highly stressed or unreliable, making them vulnerable to droughts or other climatic shocks [Saccoccia and Kuzma (2024)]. This analysis overlays global cultivation areas of four staple crops—wheat, maize, rice, and soybean—onto basin-level water stress thresholds of 80 percent, 90 percent, 95 percent, and

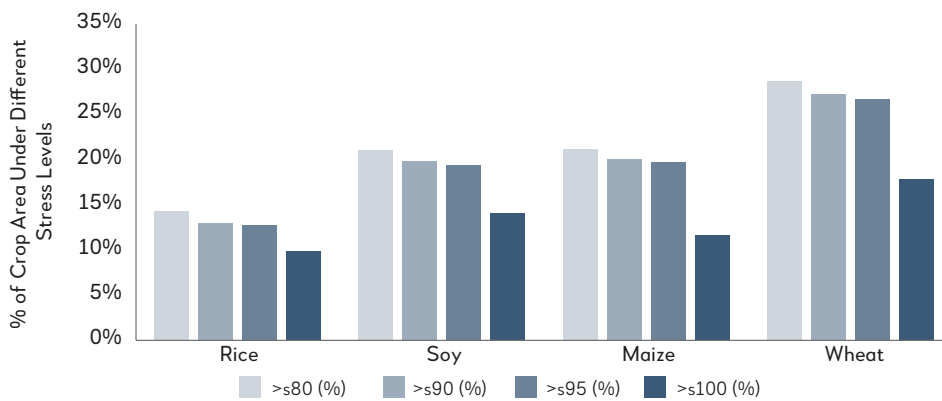
Box I *continued*

Figure I1: Spatial Distribution of Population Density and Water Stress Across Hydro Basins



Source: World Resources Institute (WRI); European Union-Global Human Settlement Layer.⁹

Figure I2: Percentage of Crop Areas Under Different Stress Levels



Source: AIB staff estimates based on Aqueduct Baseline Water Stress (World Resources Institute) and global crop yield dataset, PANGAEA

100 percent. Seen in Figure I2 wheat and maize exhibit the highest exposure with roughly one-quarter of global cultivation located in basins exceeding 80 percent stress. Rice and soybeans exhibit lower exposure but also with clusters at high stress. Figure I3 to Figure I10 present spatial distribution maps for each crop under high (>80 percent) and extreme stress (>100 percent) conditions.

Implications for Resilience

The vulnerabilities extend beyond local shortages. Basins in South Asia and the Middle East and North Africa are critical nodes in global food systems and economic networks. Rising water stress in these regions could disrupt supply chains and trigger price volatility and risks to food security. Agriculture, which accounts for 72 percent of global water withdrawals, is both a driver and a victim of water stress. Climate change will further destabilize hydrological patterns, increase flow variability, and compound scarcity [IPCC (2022)]. Strengthening resilience in these basins requires targeted investment in water-efficient infrastructure and water-secure systems, alongside governance that improves allocation and demand management across sectors.

⁹ Population counts from 100-m GHSL raster cells were aggregated to WRI basin polygons. Population density classes follow the global distribution: high (>75th percentile), medium (25-75th percentile) and low (< 25th percentile). Water-stress categories are based on Aqueduct thresholds: Extremely high stress corresponds to withdrawals exceeding 80 percent of renewable supply, moderate stress to 10 and 80 percent, and low stress to less than 10 percent.

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Box I *continued*

Figure 13: Global Wheat Area Under Water Stress (>80%)

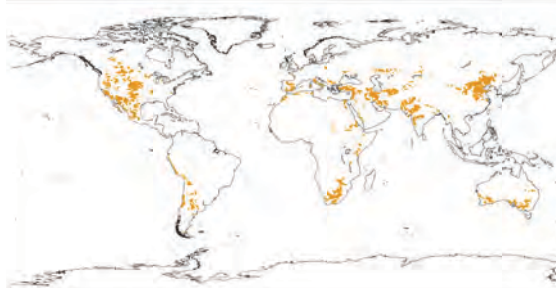


Figure 14: Global Wheat Area Under Water Stress (>100%)

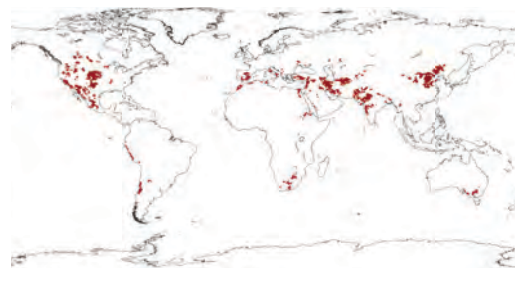


Figure 15: Global Maize Area Under Water Stress (>80%)

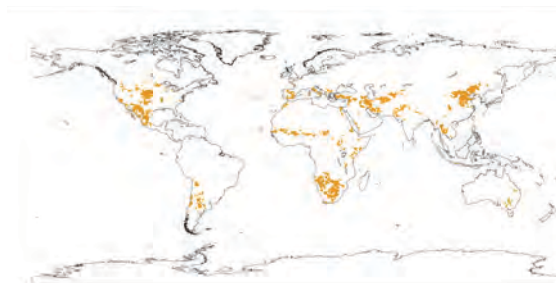


Figure 16: Global Maize Area Under Water Stress (>100%)

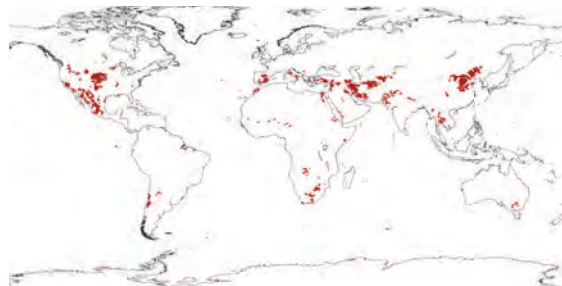


Figure 17: Global Rice Area Under Water Stress (>80%)

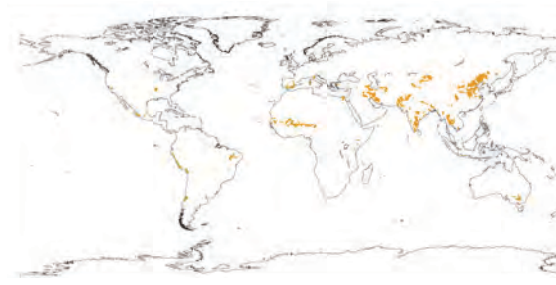


Figure 18: Global Rice Area Under Water Stress (>100%)

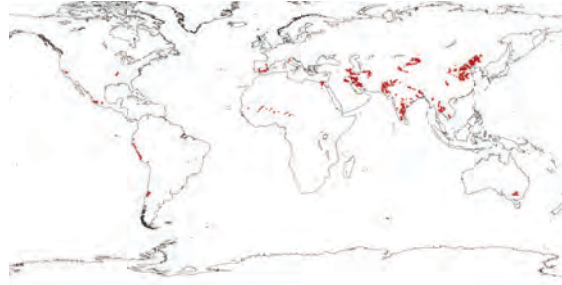


Figure 19: Global Soybean Area Under Water Stress (>80%)

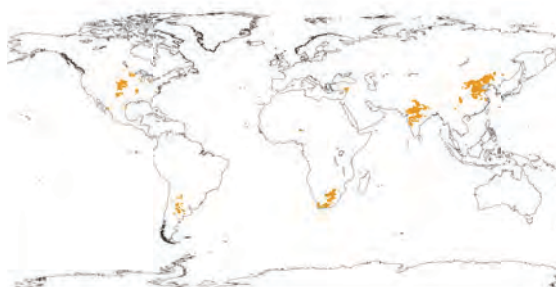
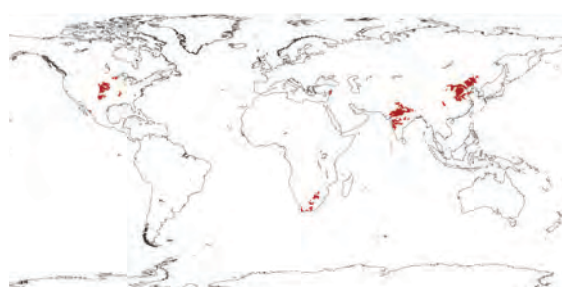


Figure 110: Global Soybean Area Under Water Stress (>100%)



Source: AIIB staff estimates.

Box J: Mapping Development Finance Flow to the Water Sector

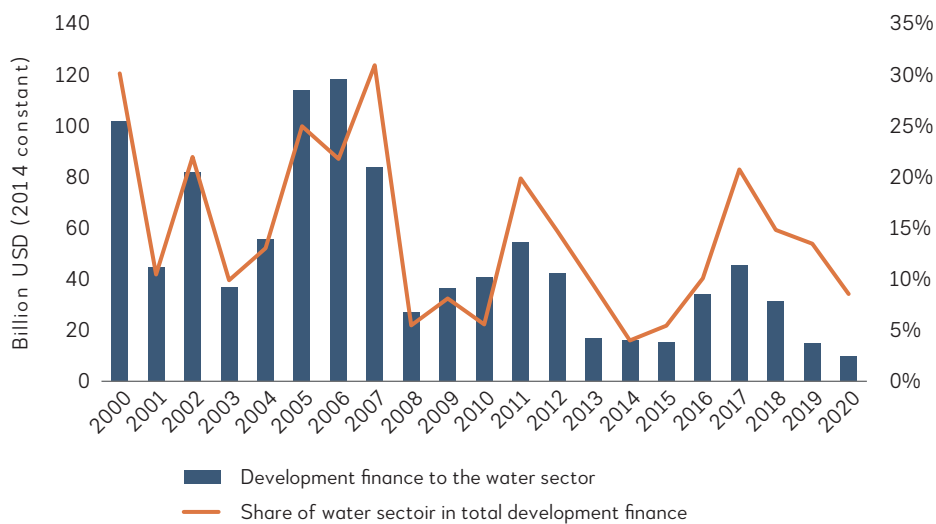
The world remains off track to meet the Sustainable Development Goals (SDGs), including SDG 6 on Clean Water and Sanitation. Achieving this goal will require sustained investment, with global costs estimated at more than USD1 trillion annually between 2015 and 2030 [Strong et al. (2022)]. A central finding of this analysis is that development assistance to the water sector is shaped more by service access gaps than by hydrological climate risk, indicating opportunities to realign resources toward resilience and long-term water security.

Official development assistance (ODA) plays an important role in bridging the financing gap for the water sector. Recent evidence shows that ODA accounts for seven percent of global spending in the water sector. With China and India excluded, the share is 13.5 percent, highlighting the role of ODA in supporting water sector development, particularly in low- and middle-income countries where domestic resources remain limited [Joseph et al. (2024)].

Drawing on a newly compiled Geocoded Official Development Assistance Dataset (GODAD), this box provides a global overview of development finance flows to the water sector, tracing their evolution over time and the factors shaping aid allocation. The dataset covers projects financed not only by traditional donors captured in the OECD Creditor Reporting System but also by emerging development partners such as China and India, along with the World Bank, the largest multilateral development bank.^a

Overall scale and trends. Between 2000 and 2020, the GODAD recorded almost 698,000 development projects, of which about 14 percent targeted the water sector. In value terms, the development financing flow to the water sector reached around USD1 trillion, accounting for about 14 percent of total financial commitments during this period.

Figure J1: Evolution of Water Sector Development Finance



Source: AIIB staff estimates.

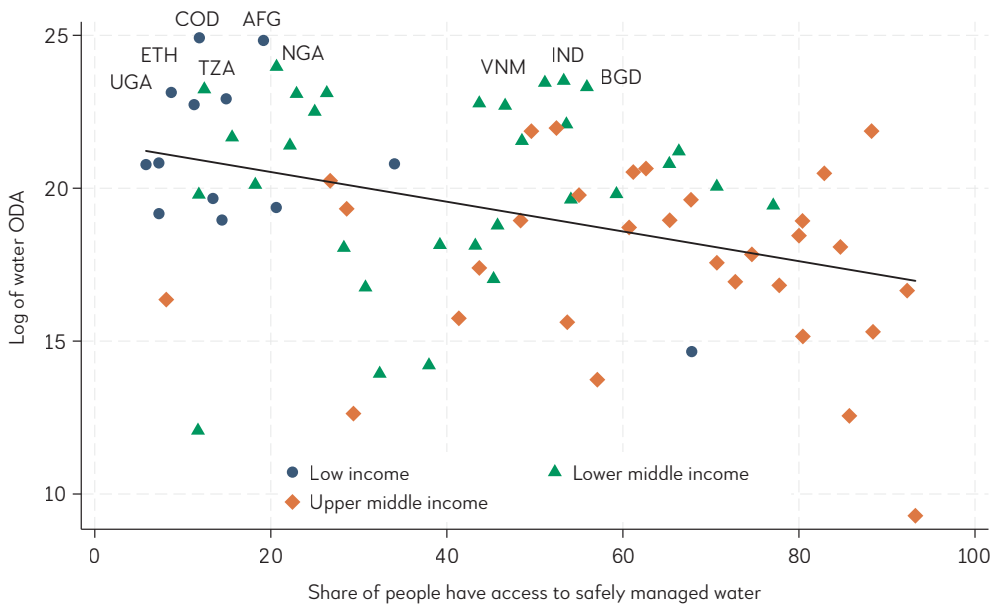
Despite water's fundamental importance, both the absolute volume and share of water-related development finance have fluctuated over the past two decades. While water remains a long-standing development priority, its relative share in total development finance has gradually declined to around 10 percent. This shift reflects rising competition from other sectors and evolving donor priorities.

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Box J continued

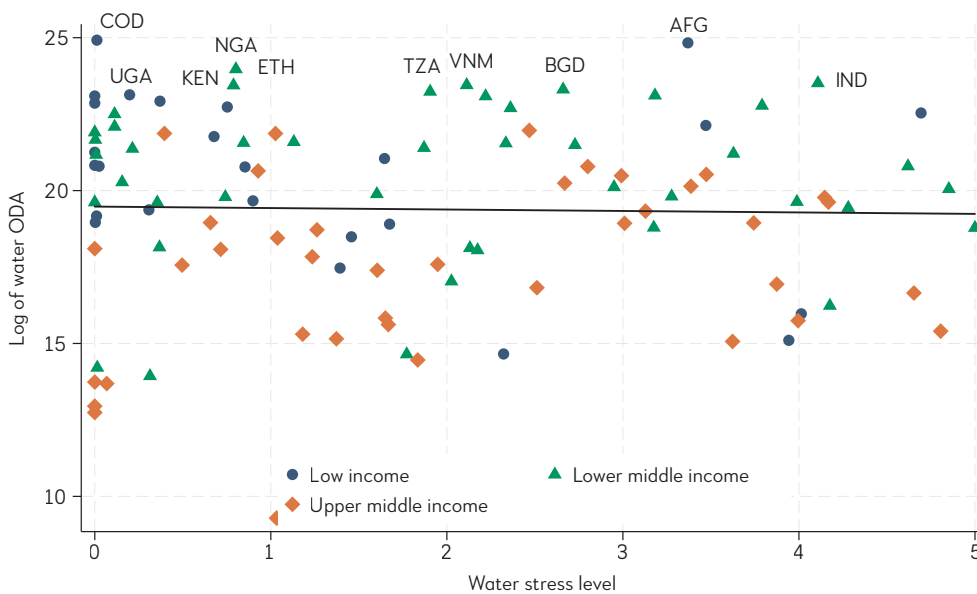
What drives water ODA flow? To better understand the factors influencing the allocation of water aid, the log of water aid value is plotted against three factors: water access, water stress, and drought risk (see figures below). A moderate negative correlation (-0.38) emerges between water ODA and the share of the population with safely managed water access, suggesting that countries with larger access gaps attract more external financing. By contrast, correlations with drought risk (0.11) and long-term water stress (-0.023) are weak.^b These patterns indicate that donor allocations tend to respond more to basic service deficits than to hydrological or climate-related stresses.

Figure J2: ODA-Like Flows to the Water Sector vs. Access to Safely Managed Water



Source: AIIB staff estimates.

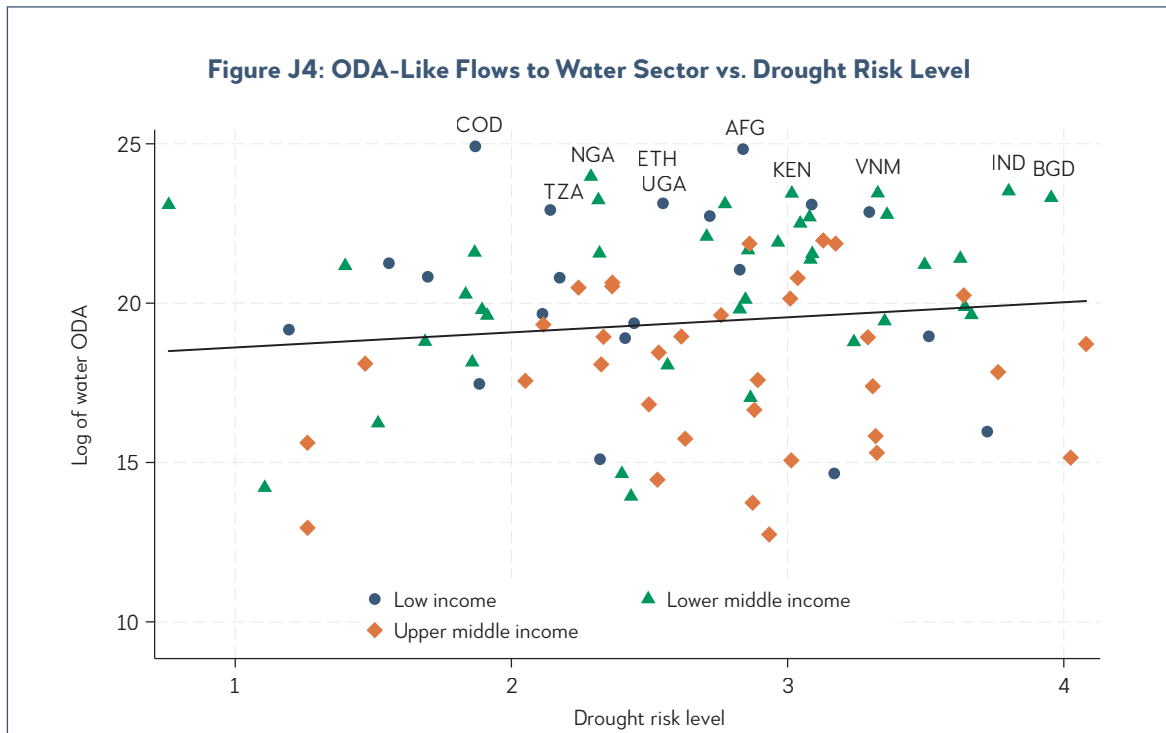
Figure J3: ODA-Like Flows to the Water Sector vs. Water Stress Level



Source: AIIB staff estimates.

continued on next page

Box J continued



Source: AIB staff estimates.

Implications for financing along the hydrological cycle. As climate change intensifies variability in the hydrological cycle, investment needs for resilient water systems will continue to rise. The current distribution of ODA, which focuses largely on access gaps rather than underlying hydrological risks, highlights an opportunity for MDBs and other development actors to better align resources with climate resilience and water security objectives. This pattern also suggests that countries with strong water access but high water stress, such as Egypt and Tunisia, may be overlooked. Expanding support to these countries is therefore important for fostering a more equitable and water-secure future.

^a The time span covers for various donors are different: 18 European donors and the United States (1973-2020), the World Bank (1995-2023), India (2007-2014), and China (2000-2021). Considering the projects from various donors have a different time period, we only look at the overlapping period of 2000-2020 to better capture trends for all countries.

^b The water stress and drought risk of each country comes from WRI Aqueduct 4.0 datasets. Baseline water stress measures the ratio of total water demand to available renewable surface and groundwater supplies. Drought risk measures where droughts are likely to occur.





CHAPTER 10

WATER ENDOWMENTS, VIRTUAL WATER TRADE, AND THE PRICING OF WATER RESOURCES

HIGHLIGHTS

- Virtual water trade can relieve water shortages via imports of water-intensive goods but can also risk water and environmental stresses for exporting countries, especially those with large agriculture sectors with heavy water use. A group of emerging economies accounts for most of the global virtual water trade.
- The availability of water (or water endowments) is not a good predictor of exports: Some countries facing high water stress continue to export virtual water. Using a gravity model analysis, water tariffs (pricing) more accurately predict the amount of virtual water countries export, especially in the agriculture sector.
- Many countries are underpricing water compared to water availability. Correcting this can improve trade and global water use. Since higher water prices will particularly affect the agriculture sector, additional support for the sector is needed.

10.1 Virtual Water Trade: Key to Water and Food Security

Virtual water trade (VWT), or the water content embedded in the production of goods for international trade that is not directly observable, has received attention in recent years. Largely hidden in global trade flows, such trade is in fact critical to many economies, with around 770 billion cubic meters of virtual water traded annually. Through “virtual water,” global trade redistributes

water embedded in agricultural and industrial production, linking national economies through the global water cycle.

While small compared to transboundary riverine or atmospheric flows, VWT is already embodied in food and goods and thus directly impacts consumption and welfare. For example, the International Water Management Institute notes that if countries in the Middle East and North Africa had to produce the wheat they import annually,

they would require 50 billion cubic meters of water, equivalent to the entire annual flow of the Nile River into Egypt.

VWT is thus critical to both water and food security, increasing water stress and rising geopolitical tensions. While VWT is key to alleviating water stress in some countries, it could also place additional strain on water resources and even lead to environmental degradation in some exporting countries. In many cases, water is not priced to cover its full extraction costs, let alone environmental costs.³⁰ This may lead to a large and potentially transboundary ecological impact [Du et al. (2022); Zhong et al. (2023); Mekonnen et al. (2024)]. These concerns have only grown due to global warming.

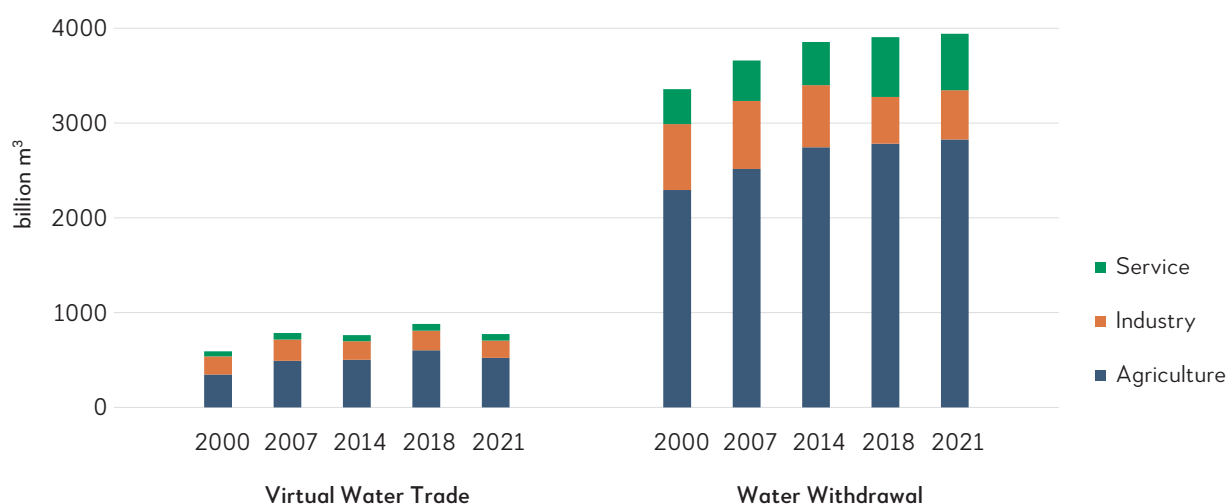
Water stress is not only impacting human welfare but also ecosystems. Excess water has reduced environmental flows, leading to environmental degradation and loss of biodiversity [Vanham, Alfieri and Feyen (2022)]. Finally, equity concerns also arise in the context of VWT: Vallino, Ridolfi and Laio (2021) show that 39 percent of virtual water exports originate from a country with higher water stress compared to the destination country, raising concerns about the fairness and sustainability of such trade.

A clear understanding of virtual water trade and the economics of water will be instructive for better water policy. This chapter examines global patterns of VWT using cross-country and bilateral data from the Asian Development Bank's Multiregional Input-Output Tables and the World Bank's World Development Indicators for water endowments and country-sector-level water withdrawals. Data on water tariffs is drawn from the International Benchmarking Network for Water and Sanitation Utilities.

10.2 Trade Pattern One: Which Sector Dominates VWT?

In 2021, the total global water withdrawal reached around 3,900 billion cubic meters, of which about 770 billion cubic meters were embodied in international trade as virtual water (Figure 32). The agriculture sector accounts for the most water directly withdrawn and contributes most to VWT. The industry sector has some withdrawals and VWT. The services sector sees direct water withdrawal, but VWT is minuscule.

Figure 32: Global Virtual Water Trade and Water Withdrawal



Notes: m³ = cubic meter.

Source: AIB staff estimates.

³⁰ See technical report by Wheeler, Nauges, and Grafton for the Global Commission on the Economics of Water (2023).

10.3 Trade Pattern Two: The Top Countries Exporting and Importing Virtual Water

The global pattern of VWT shows a clear divide between exporters and importers (Figure 33). The largest exporters include India, Indonesia, Thailand, and Viet Nam, which are all emerging and developing economies with strong agricultural bases and high dependence on water-intensive exports. In contrast, major importers such as the United States, Japan, Germany, and the United Kingdom are high-income countries that outsource much of their water-intensive production.

China and Bangladesh are exceptions among importers, reflecting their roles as manufacturing hubs in global value chains. A fuller VWT chord diagram is provided in Figure 34.

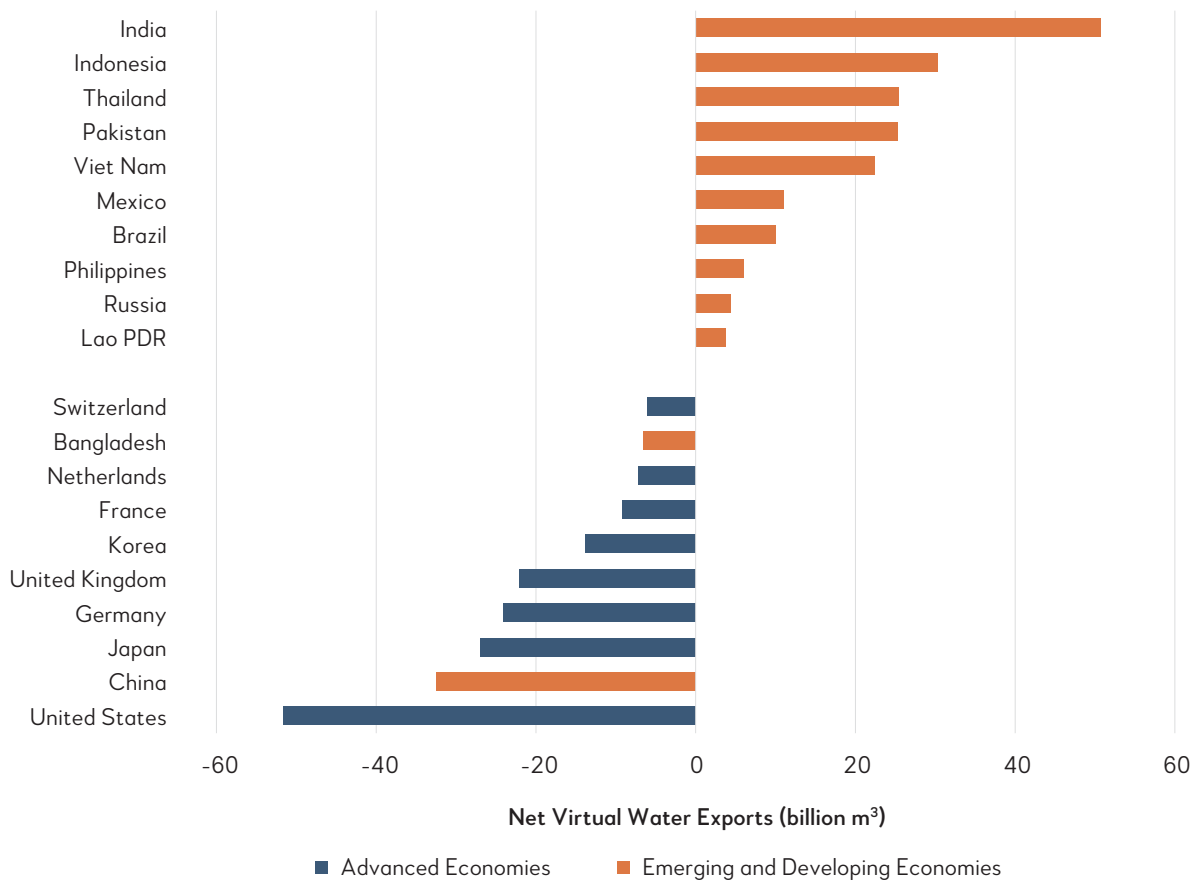
10.4 Trade Pattern Three: Do Water Endowments Determine VWT?

A common intuition behind VWT is that countries with abundant water resources should export water-intensive goods, while water-scarce countries should rely more on imports. This section examines whether this intuition is borne out in the data. The evidence suggests that while water availability matters in theory, it is not a strong predictor of observed VWT patterns in practice.

Water abundance in absolute terms

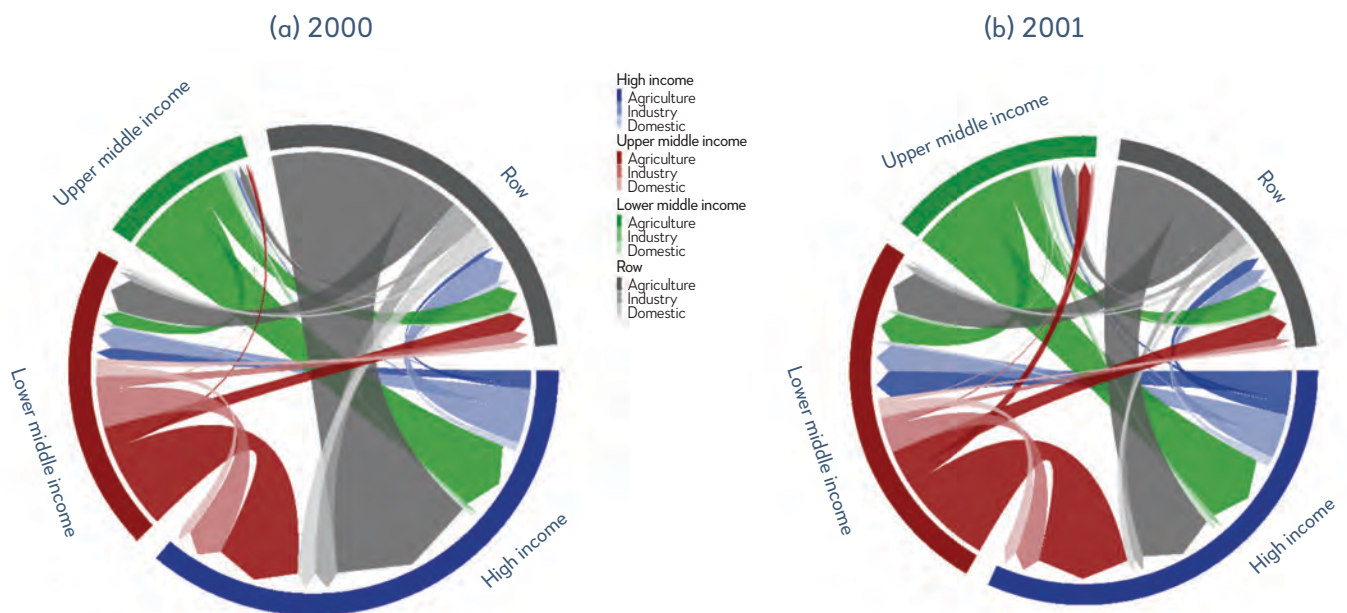
Water abundance is often assessed using water stress, defined as the ratio of total annual freshwater withdrawals to total renewable freshwater resources. The United Nations Water classifies water stress

Figure 33: Top 10 Net Exporters and Importers of Virtual Water (2021)



Source: AIBB staff estimates.

Figure 34: Net Virtual Water Exports for Different Country Income Groups by Sectors



Notes: The chord diagrams above provide detailed flows of virtual water exports. Solid boundary (near circumference of circles) indicates export origination, while arrowed boundary indicates destination (or import). For example, the agriculture sector (darkest green) in lower-middle-income countries exports significant amounts of virtual water to the agriculture, industry, and services sectors of high-income countries, while receiving comparatively little in return from these sectors in other countries. Similarly, the agriculture sector of upper-middle-income countries also exports a relatively significant amount of virtual water to the three sectors in high-income countries.

Source: AIIB staff estimates.

levels as follows: <25 percent as no stress, 25–50 percent as low, 50–75 percent as medium, 75–100 percent as high, and >100 percent as critical stress.³¹

Globally, most countries do not face water stress (Figure 35, a). Nonetheless, there is little evidence in country cross-sectional data that water-stressed countries are net importers of virtual water. In fact, there are a handful of countries that have moderate to high levels of water stress and yet are net exporters of virtual water, including India, Kyrgyzstan and Pakistan. Countries with high water use efficiency (measured by GDP per unit of water) are also likely to be net water factor importers (Figure 35, b). These patterns indicate that countries with higher water productivity tend to rely more on VW imports, while VW exporters are not necessarily water abundant.

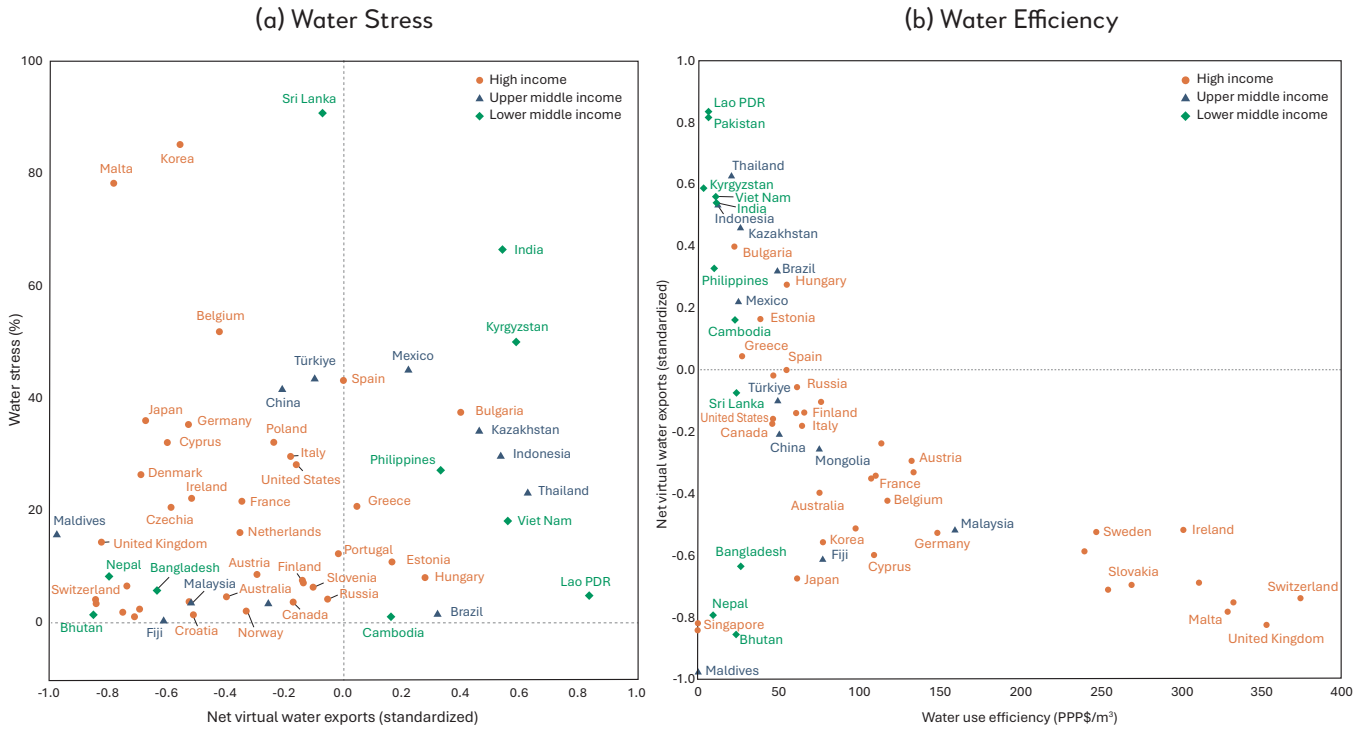
These country-level observations are consistent with broader trends. High-income countries remain net importers of virtual water with relatively low and declining water stress, while middle- and lower-income countries are consistent net exporters (Figure 36, a). On average, lower-middle-income countries face the highest water stress and are, at the same time, net exporters of virtual water to high-income countries. This provides prima facie evidence that the global VWT largely reflects production and trade specialization rather than relative water endowments. In particular, emerging and developing economies, where agriculture accounts for a larger share of output and employment, and where production is often more water-intensive, supply a substantial share of the virtual water consumed in advanced economies.

³¹ In practice, water stress manifests through declining surface and groundwater availability; increased competition among agricultural, industrial, energy, and domestic users; and growing reliance on degraded or costly water sources as withdrawals approach or exceed renewable supply [Kummu et al. (2016); Wada et al. (2011); Huang et al. (2021)]. These pressures are often compounded by water quality degradation, such as salinity and nutrient pollution, which effectively reduces usable water and intensifies scarcity even where physical water volumes remain unchanged. [Van Vliet (2021); Musie and Gonfa (2023)].

Interestingly, Brazil, as an economy with a high endowment of freshwater, became a net virtual water exporter as its agriculture sector expanded, with no perceptible impact on its water availability

(Figure 36, b). This underscores the beneficial effects of VWT. China, on the other hand, moved from being a virtual water exporter to an importer within the past two decades.

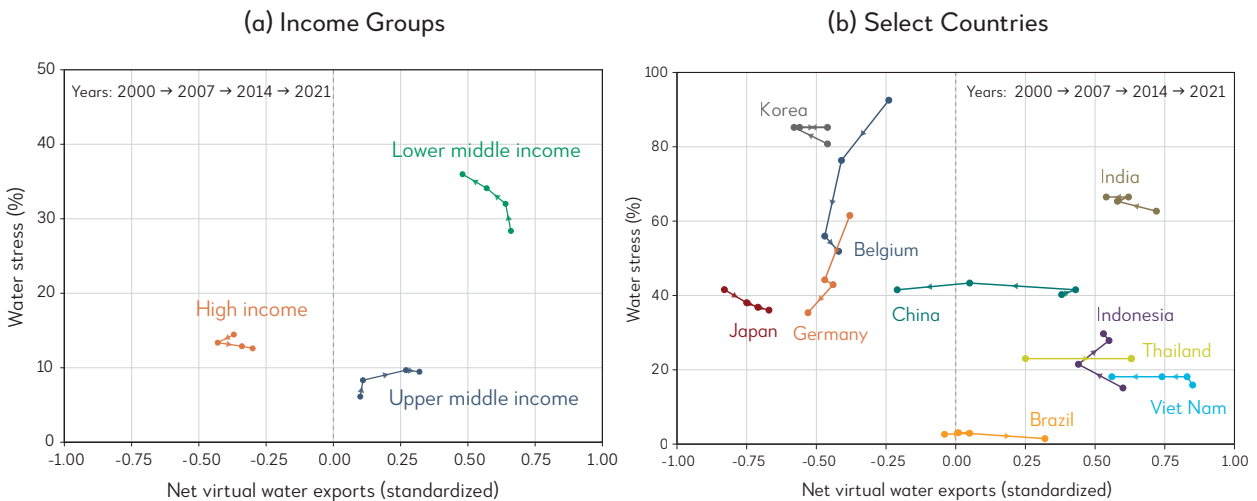
Figure 35: VWT and Water Use Indicators (2021)



Notes: Net virtual water export (standardized) is defined as net virtual water exports divided by total virtual water trade. Pakistan's water stress is estimated to exceed 100 percent and is not shown in this figure.

Source: AIB staff estimates.

Figure 36: Water Stress and Net Virtual Water Exports by Income Groups and Select Countries



Source: AIB staff estimates.

Bilateral trade patterns also reinforce this conclusion: 54 percent of country-pairwise trade shows that a country with higher water stress provides more virtual water exports to a country with lower water stress. Similarly, 52 percent of pairwise trade cases show that a country with lower freshwater per capita provides more virtual water exports to a country with higher endowments.³²

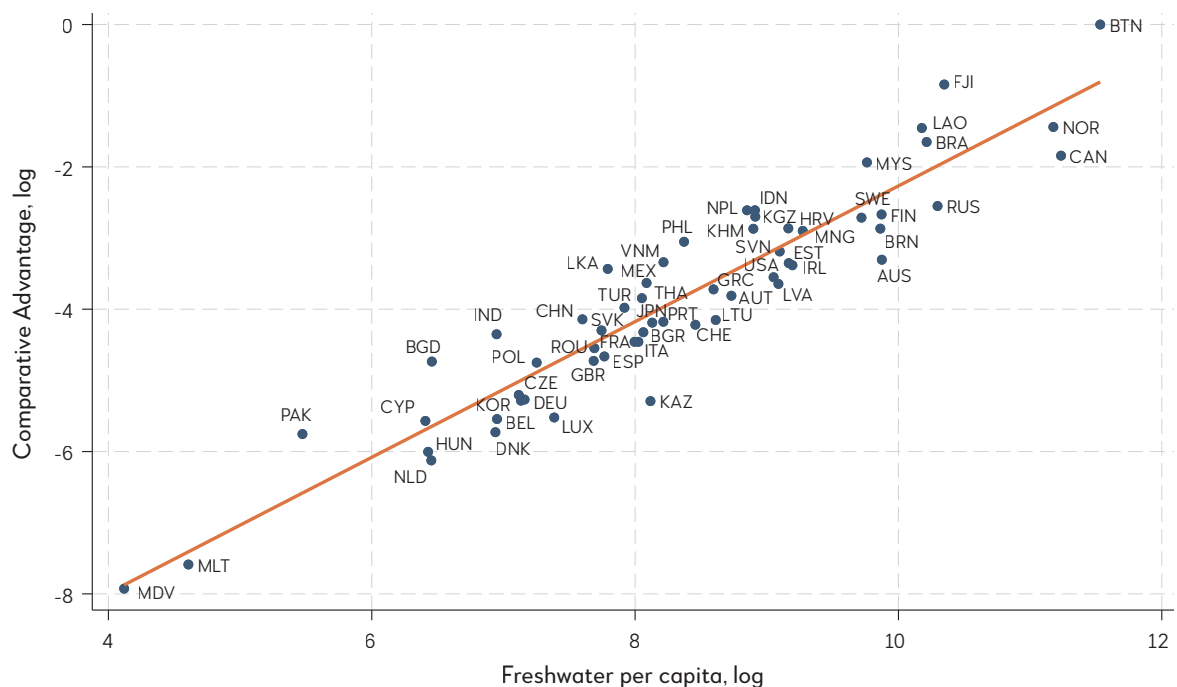
**Water abundance in relative terms:
Comparative advantage**

While absolute water abundance shows limited influence over a VWT pattern, trade theory suggests that what matters is relative abundance. In a generalized Heckscher-Ohlin framework, Deardorff (1982) shows that, in theory, countries will on average be net exporters of their relatively abundant factors and importers of relatively scarce factors. Hence, the HO logic does not rule out the fact that water-stressed economies may be net

virtual water exporters. This phenomenon does not require factor intensity reversal, differences in technology, or preferences (issues commonly discussed in the trade literature). Rather, there can be divergence between comparative and absolute advantage in a classical sense—a country can export a scarce factor because other factors are even scarcer, relatively speaking. For example, emerging and developing economies may well specialize in agriculture that requires high water intake even when water-stressed because they are comparatively disadvantaged in other sectors.

A simple scatter plot shows a strong alignment between countries' absolute water endowments and their comparative advantage in water, measured following the methodology of Kang et al. (2007) to derive a Euclidean distance-based measure of factor abundance [Figure 37].³³ It is striking how well comparative advantage aligns with absolute advantage, defined as freshwater per capita (correlation 0.94). The alignment between

Figure 37: Correlation Between Water Comparative and Absolute Advantage



Notes: The Y axis shows the comparative advantage of water based on Kang et al. (2007). Freshwater per capita (log) is used as the measure of absolute advantage on the X-axis.

Source: AIIB staff estimates based on Penn World Table and FAO.

³² These figures are higher than 39 percent reported by Vallino, Ridolfi, and Laio (2021) as this research includes all sectors (not just agriculture).

³³ Detailed methodology in Appendix 6.

Table 10: Regressions of Country Aggregate Net Virtual Water Exports

Variables	(1) Net Export Standardized	(2) Net Export Standardized	(3) Net Export Standardized
Log Water Endowments Per Capita	-0.125 (0.154)		
Log Comparative Advantage in Water		0.0211 (0.0242)	
Log Water Tariff (15 m ³)			-0.0225* (0.0121)
Constant	0.797 (1.273)	-0.181* (0.0982)	-0.119*** (0.0337)
Observations	900	639	469
R-squared (Overall)	0.960	0.953	0.956
R-squared (Within)	0.00364	0.00150	0.00464
F-statistic	0.654	0.761	3.458
p-value	0.422	0.387	0.0685
Number of Countries	60	60	60
Country Fixed Effects	Yes	Yes	Yes

Notes: Clustered standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Source: AIB staff estimates.

comparative and absolute advantage implies that there are no significant groups of countries with poor water endowments that are nonetheless “trapped” in exporting VW because other resources are relatively scarcer.

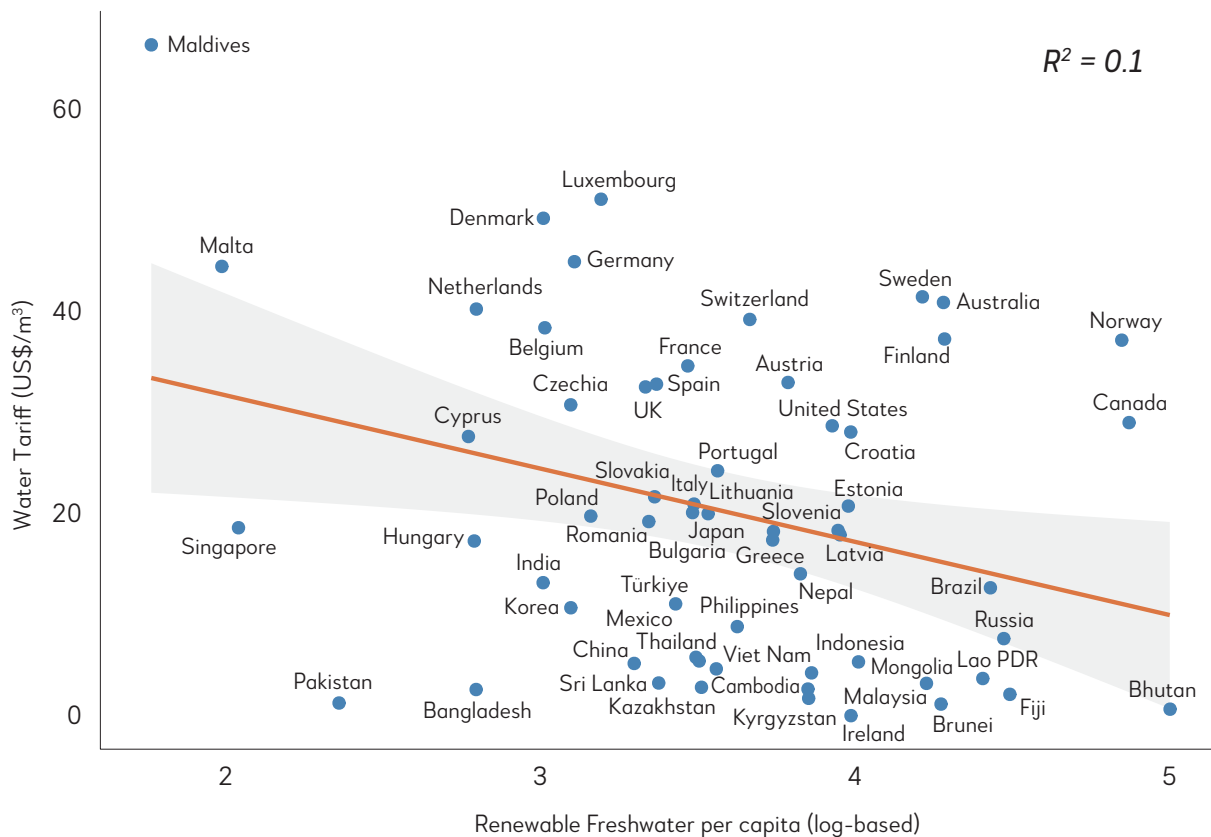
While the positive correlation between absolute and comparative advantage holds on average across countries, the research also reveals that South Asian countries do not have an absolute advantage that matches up to their comparative advantage, underscoring the relatively poor water endowments in that region. The implications of this gap are particularly severe for India, Pakistan, and Bangladesh, where absolute water availability is already low. In such a context, moderate gaps between comparative and absolute advantage translate into disproportionately higher pressures on water resources and exacerbate existing water stress.

Further empirical evidence also suggests that water endowments, whether measured in absolute or relative terms, do not, on their own, help explain the VWT patterns. This observation is also reinforced by

regression analysis in Table 10. The table presents regression results for countries’ aggregate virtual water trade balances. The dependent variable is a standardized measure of net virtual water exports, defined as gross virtual water exports minus imports, divided by total virtual water trade. The results show that both absolute water endowments (measured by freshwater availability per capita) and comparative advantage in water are not statistically significant predictors of a country’s net virtual water export position. In other words, countries with more water are not more likely to be net exporters of virtual water.

10.5 Trade Pattern Four: Does Water Pricing Influence VWT?

If water endowments do not fully explain observed trade patterns, the question becomes: what factors do? One key candidate is water pricing. Unlike natural endowments, water tariffs are a policy variable that directly affects production costs and incentives in water-intensive sectors.

Figure 38: Water Tariffs (15 m³) and Renewable Fresh Water Per Capita

Source: AIB staff estimates.

Many countries adopt volumetric tariffs with an increasing block tariff design, where the price of water increases with usage levels. Hence, the data on water tariffs are collected across three tiers (15, 50, and 100 cubic meters). For this chapter, water tariff refers to the first-tier price based on 15 cubic meters, as this is most likely the most common and hence the most representative water price experienced by households and businesses.

Across countries, there is generally a negative correlation between water abundance and water tariffs in the cross-section, though substantial heterogeneity remains (Figure 38). Countries such as Pakistan, Bangladesh, and India have relatively low per capita renewable freshwater resources, yet maintain low water tariffs across a range of tariff levels. This may contribute to continued water-intensive exports despite the water stress in India and Pakistan. In contrast, countries like Singapore and the Netherlands, among others, which face similar or even lower water availability, impose higher tariffs that encourage more efficient use.

Bilateral trade patterns are consistent with this interpretation: Only 37 percent of country pairwise trade shows the exporter to have a higher water tariff than the importing country. In most cases, virtual water flows from countries with lower water tariffs to those with higher tariffs. This suggests that water pricing, rather than water endowments, is a better predictor of the direction of virtual water trade.

The regression results in Table 10 further reinforce this conclusion. While measures of water endowment and comparative advantage show little explanatory power, water tariffs are negatively and significantly associated with aggregate net virtual water exports. Countries that price water more cheaply tend to export more virtual water, all else equal.

To assess whether this relationship also holds at the bilateral level, the analysis extends to a simplified gravity-model framework that relates bilateral virtual water trade balances to differences in water tariffs between exporter and importer, while

Table 11: Instrumental Variable Regressions for Bilateral VWT Balances

	Bilateral VWT Balance, logs			
	(1) Total Trade	(2) Agriculture	(3) Industry	(4) Services
Diff Log Water Tariff (15 m ³) IV: Diff Log Freshwater Per Capita	-1.749*** (0.580)	-1.470*** (0.561)	0.733** (0.343)	-1.608*** (0.572)
Log Exporter Water Productivity	-1.116*** (0.133)	-0.815*** (0.143)	-0.739*** (0.0833)	-0.926*** (0.139)
Log Importer Water Productivity	0.805*** (0.0783)	0.439*** (0.0908)	0.732*** (0.0522)	0.724*** (0.0804)
Log Exporter GDP	0.981** (0.430)	0.342 (0.432)	-0.561** (0.257)	1.136*** (0.424)
Log Importer GDP	-0.961** (0.395)	-0.463 (0.410)	0.618** (0.251)	-1.043*** (0.396)
Constant	0.994 (9.385)	5.388 (8.993)	-1.772 (5.559)	-1.549 (8.997)
Observations	8,185	8,185	8,185	8,185
R-squared	0.865	0.918	0.897	0.660
F-statistic (Overall Regression)	266	348.9	263	103.9
Exporter Fixed Effects	Yes	Yes	Yes	Yes
Importer Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes

Notes: Clustered standard errors at trade-pair level in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Source: AIB staff estimates.

controlling for market size and country-specific characteristics through fixed effects. This approach allows the analysis to isolate the role of water pricing without explicitly modeling trade costs, technology differences, or other production inputs, which are absorbed by exporter and importer fixed effects.³⁴

Table 11 reports the results from instrumental-variable regressions of bilateral virtual water trade balances. To address potential endogeneity in water tariffs, freshwater endowments per capita are used as an instrument. While water endowments are correlated with water tariffs across countries, they do not directly predict aggregate virtual water exports, making them a suitable instrument in this context.

The results show a strong and statistically significant negative relationship between water tariff differences and bilateral virtual water trade. At the aggregate level, a higher water tariff in the exporting country relative to the importing country is associated with substantially lower virtual water exports. This effect is particularly pronounced in agriculture, which accounts for the bulk of global virtual water trade. The estimated coefficients imply plausible water cost shares in agricultural production and align well with existing estimates of substitution elasticities from the literature, lending credibility to the empirical approach.

³⁴ Formal model, assumptions, and estimation strategy are described in Appendix 6.

The negative and significant coefficients for total trade and agriculture indicate that water pricing meaningfully affects both the extensive and intensive margins of virtual water trade. Services also exhibit a negative and significant relationship, while the results for industry are weaker and less stable, reflecting lower water intensity and greater scope for substitution in industrial production.

10.6 Concluding Remarks

Virtual water trade has the potential to alleviate water shortages in regions by allowing the import of water-intensive goods, especially in agriculture. It has the potential to enhance both water and food security. But clearly, VWT can also compound water stress in some exporting countries. Given increasing water stress in many countries amid climate change and other environmental stresses, a better-functioning global VWT system could more efficiently use water resources and allocate production.

The chapter shows that comparative advantage in water aligns well with water endowments. Hence, in principle, Heckscher-Ohlin-driven virtual water trade can direct the production and export of water-intensive goods toward countries with more water, thereby improving global water use. However, water-endowed countries are generally not net exporters of virtual water. Instead, developing and emerging economies, including some facing water stress, tend to export water, mainly due to specialization in agriculture, the largest direct user of water and the source of most VWT.

Building on the gravity model, the regression results show that agricultural exports decline as water tariffs increase, and that this relationship is statistically significant. Water tariffs at appropriate levels can thus significantly impact agricultural exports and water use.

Specialization in agriculture, even if water-intensive, is not inherently negative. However, many countries have water tariffs that are noticeably below the global cross-country benchmark. The underpricing of water appears particularly acute in a select group of countries, resulting in large exports of virtual water despite moderate to high levels of water stress.

A suitable tariff that reflects local scarcity is key to restoring trade patterns that better reflect actual water constraints and to improving the efficiency of global water use. Nonetheless, as agriculture is the largest user of water, higher water tariffs will have a large impact on the sector, especially in developing economies, underscoring the need for complementary support measures.

Finally, the model considers only short-run responses, focusing on reduced water use in production and lower exports as prices adjust. The estimated response is therefore likely to understate longer-run effects. Over time, higher water tariffs can also generate efficiency gains by encouraging investment in water infrastructure and technology.



CHAPTER 11

GOVERNING WATER IN THE AGE OF EXTREMES

ADDRESSING TOO MUCH, TOO LITTLE, TOO DIRTY, AND TOO UNEQUAL

11.1 Global Water Cycle Governance

Water lies at the intersection of human development, economic activity, and ecosystems, shaping the quality and sustainability of each while operating simultaneously at the local, regional, national, and global levels. As a result, water governance is inherently complex and multi-scalar. It is frequently fragmented across institutions and sectors, creating overlapping mandates, weak coordination, accountability gaps, and inequitable access. These dynamics reflect historical approaches to water that prioritized technical control and sectoral development over integrated and socially embedded governance.

Across societies, water systems—from rivers and aquifers to wetlands, rainfall regimes and water stored in forests and plants—function as archetypal public goods: essential to life and livelihoods, highly interdependent, vulnerable to overuse, and impossible for any single actor to manage alone. When these systems are governed effectively and supported by sustained investment, the benefits are substantial, as demonstrated by the dramatic reductions in child mortality and gains in life expectancy following the expansion of piped water and sanitation in Europe and North America [Alsan and Goldin (2019)] and by more recent improvements in health, productivity, and education in countries such as Brazil, India, and parts of East

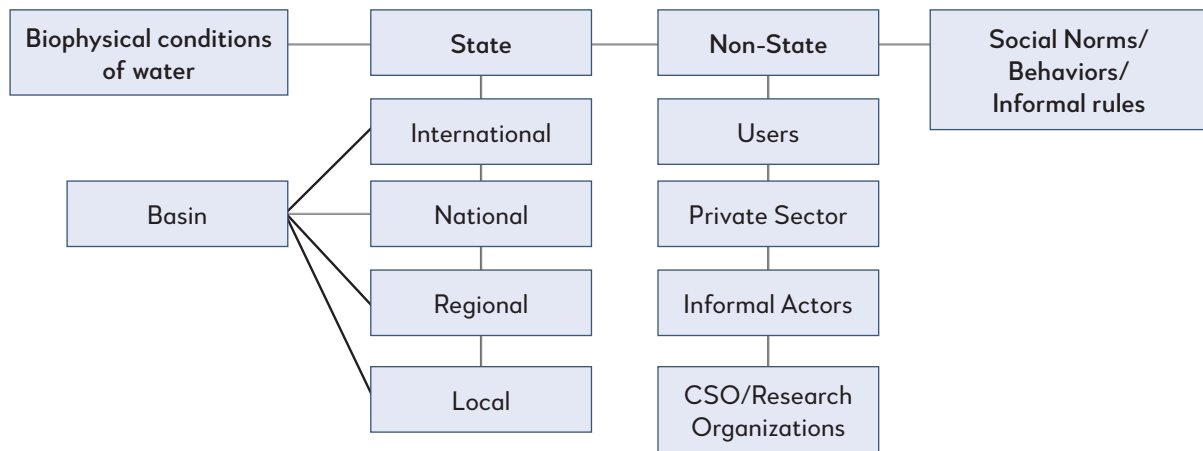
Asia [Ranjan (2025); Joshi and Amadi (2013); Santiago Ortiz-Correa et al. (2016)]. Over longer historical periods, irrigation has helped societies manage drought and rainfall variability from ancient Mesopotamia to modern California, while hydropower has supported industrialization in places as diverse as Norway and the Tennessee Valley. Despite this strong and well-documented record, water's potential as a driver of inclusive and sustainable development remains largely unfulfilled in much of the developing world.

This chapter begins with a simple premise: Water issues are rarely only physical problems and are more often failures of governance. Understanding how pricing, subsidies, nature degradation, and inclusion shape access to water is essential to unlocking its potential as a driver of equity, resilience, and sustainable development.

The Multi-Scalar Water Governance System

Water governance operates within social-ecological systems (SES)—integrated systems in which biophysical processes (such as hydrology, climate dynamics, soils, and ecosystems) interact continuously with social processes, including governance structures, institutions, norms, technologies, and human behaviour. These elements

Figure 39: Actors in Water Governance



Source: AIIB staff estimates.

are interconnected through feedback loops, meaning that neither the social nor ecological dimensions can be meaningfully understood in isolation [Ostrom (2009)]. It depends on a constellation of factors: the biophysical characteristics of water systems, formal and informal rules, operational practices, actor relationships, enforcement arrangements, and ongoing processes of learning and evaluation. Consequently, assessing water governance requires using multiple indicators.

Common evaluation dimensions include:

- Effectiveness, referring to clear roles and responsibilities, alignment with basin-scale dynamics, policy coherence, and institutional capacity;
- Efficiency, encompassing data and information systems, financing arrangements, regulatory quality, and the uptake of innovative governance approaches; and
- Trust and engagement, which relates to monitoring and evaluation, management of trade-offs among users (e.g., rural versus urban or across generations), stakeholder participation, and standards of integrity and transparency [OECD (2015)].

Water governance within state structures is further characterized by its multilevel nature, spanning global institutions, national frameworks, subnational authorities, and community-level arrangements.

International Level

International water governance relies on legal frameworks and agreements that guide cooperation across more than 260 shared river basins and 450 aquifers [Hossen et al. (2023)]. Conventions such as the UN Watercourses and UNECE Water Convention, along with regional basin treaties, set rules for allocation and dispute resolution, supported by multilateral development banks (MDBs), UN agencies, and regional bodies that reinforce norms and institutional capacity.

National Level

Many countries embed water in their constitutions—as a public trust, national resource, or fundamental right—supported by national policies and legal frameworks governing its allocation, quality, and protection. These laws are implemented through ministries, regulators, coordination bodies, and national information systems. Governments also use economic tools such as tariffs, subsidies, and incentives to promote efficiency and reuse, alongside planning instruments such as basin plans, permits, and water-rights systems. Public investment in water supply, sanitation, irrigation, and risk management provides the system's infrastructure, while monitoring networks and participatory processes to strengthen transparency and accountability.

Subnational and Regional Level

Provinces and states implement water laws, manage regional basins, coordinate with municipalities, and regulate groundwater—functions that are especially important in federal systems where subnational authorities hold significant water responsibilities. Basin-level governance manages resources along natural river basins that cross administrative and sometimes national boundaries. The Mekong River offers a clear example: The Mekong River Commission coordinates cross-border planning and data sharing, while the National Mekong Committees align basin priorities with domestic policies [Mekong River Commission (n.d.)].

Local and Municipal Level

At the city and community levels, water governance directly intersects with daily human needs: drinking water supply, sanitation, stormwater drainage, and wastewater management. Municipalities and urban utilities decide how much water is produced, how it is distributed, how tariffs are set, and how networks are maintained. For example, eThekweni Municipality in South Africa is recognized for its innovative service delivery, including decentralized sanitation systems in informal settlements [Carbonell et al. (2023)]. In rural and peri-urban areas, community-managed systems—such as village water user committees in Nepal or community borehole management in Kenya—play a central role in operations and maintenance [Singh et al. (2020); Amwayi Akosi and Muiruri Kariuki (2022)].

Non-State Actors

Water governance involves a wide range of actors beyond the state. These include community groups and water users, as well as private utilities and industries whose role in innovation, efficiency, and data systems is growing. Further informal providers, such as tanker operators and customary authorities, are often essential in low-income and rapidly urbanizing areas. Civil society and research organizations also contribute to advocacy, accountability, and inclusion. Effective governance must recognize this diversity and establish mechanisms for coordination, participation, and oversight.

11.2 The Four Dimensions of Water Risks and Governance Implications

Water governance today must confront a paradox: The world is experiencing simultaneous crises of *too much, too little, too dirty, and too unequal* water. As the global hydrological cycle becomes increasingly destabilized by climate change, the same regions can experience catastrophic floods and prolonged droughts, while others face chronic scarcity alongside severe contamination.

Too Much: Governing Floods and Water Excess

Too much water refers to the increasing frequency and intensity of floods, storm surges, and extreme precipitation events as the global hydrological cycle becomes more energetic and unpredictable. Climate change, rapid urbanization, and degraded ecosystems are driving more frequent and severe floods worldwide. Expanding cities, paved surfaces, and settlement in floodplains overwhelm drainage systems, while extreme rainfall now exceeds the design limits of existing infrastructure. As a result, over a billion people face high flood risk, especially in fast-growing African and Asian cities [Zhang and Wen (2025)].

Governance Solutions

- **Restore Natural Buffers**

Floodplain and wetland restoration, mangrove protection, and upstream reforestation reduce runoff, absorb excess water, and lower flood peaks. Effective governance relies on land-use zoning, payment-for-ecosystem services and other nature finance mechanisms, and community-led restoration.

- **Build Climate-Resilient Grey Infrastructure**

Drainage systems, levees, embankments, retention basins, and pumping stations must be redesigned for future climate extremes. Updated design standards, climate stress-testing, and integrated urban water plans ensure these systems keep pace with rising hazards.

- **Advance Smart and Digital Flood Governance**

AI forecasting, real-time monitoring, GIS flood-risk maps, and early-warning systems improve preparedness and response. Open data, interagency coordination, and targeted investments in vulnerable areas strengthen effectiveness.

- **Embed Risk-Informed Land-Use Planning**

Limiting development in high-risk zones, enforcing building codes, protecting natural drainage channels, and supporting safe resettlement help reduce exposure. These measures depend on coordination between water, land, and housing authorities.

- **Expand Financial Risk Transfer**

Catastrophe bonds, parametric insurance, and public-private partnerships provide rapid financing after floods and protect households and farmers. Linking insurance to risk-reducing actions increases resilience and coverage.

China – Sponge Cities

China's Sponge City Program shifts urban flood management from rapid drainage to the absorption and reuse of stormwater through green roofs, permeable pavements, wetlands, and retention ponds. Piloted in 30 cities, the program aims to have 80 percent of urban areas retain 70 percent of rainfall by 2030 [Chikhi et al. (2023)]. Wuhan's restored lakes and wetlands cushioned the 2020 Yangtze floods [Wei et al. (2020)], though maintenance and landuse pressures remain challenging.

Kenya – Tana River Basin

Kenya's integrated flood management aligns dam operations, watershed restoration, floodplain mapping, and community early-warning systems. Coordinated releases from major dams and upstream ecosystem restoration have reduced downstream flood impacts. The approach replaced decades of damaging dam miscoordination by linking hydropower operators, irrigation schemes, and upstream forest restoration [Water Resource Management Authority (2023)]. Basin-wide rules for the Masinga and Kamburu Dams now flatten peak flows, demonstrating one of East Africa's most integrated flood-governance models.

Too Little: Managing Scarcity and Competing Demands

Freshwater scarcity is intensifying due to climate variability, rising demand, and unsustainable withdrawals. Today, two to three billion people face shortages for at least one month annually [UNICEF (2020)], and nearly two billion lack safely managed drinking water [United Nations (2024)]. Groundwater is being depleted faster than replenishment in key aquifers, from India's northern plains to California's Central Valley. Droughts are more prolonged and more severe—2024 saw extreme droughts in the Amazon, Southern Africa, and northern South America, causing wildfires, crop losses, and ecosystem damage. Agriculture—which accounts for roughly 70 percent of freshwater withdrawals—faces rising pressure as global food demand increases by up to 60 percent by mid-century [FAO (2025);United Nations (2013)]. By 2050, over half the global population may face water scarcity annually, threatening agriculture and food security [Harvey (2024)].

Governance Solutions

- **Reform Water Allocation and Improve Efficiency**

Modernized water rights, volumetric metering, and water trading ensure equitable allocation and reduce waste. Incentives for efficient irrigation, such as drip systems and soil moisture sensors, enhance agricultural water use.

- **Promote Demand Management and Behavioral Change**

Tiered tariffs, urban leak repairs, rainwater harvesting, low-flow appliances, and public awareness campaigns encourage conservation while protecting low-income users.

- **Enhance Water Harvesting, Storage, and Reuse**

Decentralized tanks, micro-dams, rooftop collection, and managed aquifer recharge stabilize seasonal availability and improve treated wastewater reuse, reduce withdrawals and support agriculture, industry, and emergency supply.

- **Design Incentives to Support Climate-Resilient Agriculture**

Drought-tolerant crops, soil conservation, agroforestry, and shifts away from water-intensive crops and from meat and dairy production toward alternative foods reduce pressure on scarce resources and strengthen food-system resilience. Incentive systems can support this shift.

- **Expand Desalination Where Appropriate**

Renewable-powered desalination complements supply in arid regions. Effective governance integrates environmental safeguards, energy management, and planning alongside other supply options.

- **Strengthen Preparedness and Early Warning**

Drought monitoring, climate forecasts, contingency funds, and community-based water tracking improve response and reduce losses.

- **Improve Groundwater Governance**

Integrated aquifer management, recharge-zone protection, watershed restoration, and community regulation, as in India's Model Groundwater Bill, build long-term resilience and sustainability.

Drought Management

Niger's 3N Initiative ("Les Nigériens Nourrissent les Nigériens") offers a strong example of drought-resilient governance in a low-income context [Kalidou et al. (2024)]. Since 2011, the initiative has restored more than five million hectares of land through farmer-managed natural regeneration, contour bunds, and half-moon structures—substantially increasing soil moisture and shallow groundwater levels. Decentralized water committees and improved coordination between local and national institutions have strengthened management of wells, grazing areas, and seasonal scarcity. Niger's enhanced Early Warning System integrates rainfall, vegetation, and market data to anticipate shortages and trigger early action. Together, these measures have increased agricultural productivity, diversified livelihoods, and reduced vulnerability, demonstrating how low-income countries can build drought resilience by aligning governance, hydrological-cycle management, and nature-based solutions.

Too Dirty: Pollution, Wastewater, and Unsafe Water Quality

Water quality is worsening due to industrial effluents, untreated sewage, agricultural runoff, emerging contaminants, and climate-driven warming. Nearly one in four people drink fecal contaminated water, causing around one million deaths annually due to diarrhea [WHO (2023)]. Rising temperatures worsen algal blooms and treatment efficacy, while persistent pollutants like PFAS, plastics, and industrial chemicals contaminate rivers and lakes worldwide. Agriculture remains the largest source of diffuse pollution. Weak enforcement, inadequate wastewater treatment, and fragmented governance exacerbate risks, making water pollution a critical public health, environmental, and industrial challenge.

Governance Solutions

- **Strengthen Pollution Regulation and Enforcement**

Effective pollution control combines clear standards, enforceable discharge limits, independent regulators, and online monitoring to ensure compliance. Expanding wastewater treatment—through decentralized systems, industrial pre-treatment, and natural methods—reduces untreated discharges. Agricultural runoff is managed with nutrient planning, buffer strips, wetlands, and precision farming. Successful examples include India's Clean Ganga Mission, the EU Water Framework Directive, China's expansion of urban wastewater treatment, and Colombia's and Kenya's integration of natural treatment systems.

- **Manage Emerging Contaminants**

Bans, advanced treatment, monitoring, and Extended Producer Responsibility curb PFAS, microplastics, and pharmaceuticals. Examples: US EPA PFAS Roadmap; EU PFAS restrictions.

- **Enhance Data, Transparency, and Accountability**

Open water-quality dashboards, citizen monitoring, and digital registries strengthen compliance and public trust. Applied in South Africa, Brazil, and China.

- **Use Economic Incentives**

Polluter-pays principles, taxes, tradable permits, subsidies, and green financing encourage cleaner production. Examples: Korea, France, China, Chesapeake Bay nutrient trading, Singapore effluent credits.

- **Expand and Reform Water, Sanitation, and Hygiene (WASH) Systems**

Decentralized WASH delivery—through rainwater harvesting, solar pumps, and community management—improves rural and urban coverage. Financing can be strengthened by bundling WASH into broader water or development projects, using public investment, PPPs, and household-level mechanisms.

- **Build Capacity for Integrating Nature-Based Solutions into Pollution Control**

Wetlands, riparian buffers, reforestation, and floating treatment systems filter pollutants, improve water quality, and reduce pressure on built infrastructure.

Too Unequal: Rethinking Water Systems for Inclusive Resilience and Wider Benefit

Dirty Water, Deep Inequality: How Pollution Fuels Exclusion

The impacts of unsafe water, sanitation, and hygiene are heavily borne by women, children, and low-income households, who shoulder disproportionately high time losses, health risks, and income penalties when water systems fail or climate extremes degrade water quality [WHO (2019)]. Women are highly exposed due to domestic roles and menstrual hygiene needs, while children are particularly vulnerable to waterborne diseases because their organs and immune systems are still developing, and they eat, drink, and breathe more relative to their body size, magnifying the exposure to pollutants [Harvard Center for Climate, Health, and the Global Environment (2025)].

Research in Bihar, India, show that prolonged flood-related contamination led to spikes in diarrheal disease, forcing women to spend hours daily on caregiving and water collection, reducing household earnings and deepening poverty cycles [Raman (2022)], while menstrual hygiene management challenges linked to poor water quality were associated with school absenteeism and workplace productivity losses, reinforcing structural inequalities in education and employment.

Costs associated with collecting, pumping, treating, storing, and purchasing water also hit poor households hardest, and are estimated to constitute 15 percent of income for lower-income households in some parts of India [Amit and Sasidharan (2019)]. In cities such as Nairobi or Lagos, residents of informal settlements may pay many times more per liter to water vendors than wealthier households pay for subsidized piped connections. The poorest, therefore, receive less water, pay more for it, and benefit least from public spending. Such losses for women, children, and poor households manifest as recurrent health shocks, lower productivity, and long-run human-capital erosion.

Nature and Inclusion: The Hidden Nexus of Climate Resilience

Chapter 7 highlights the role of forests and upstream land management in hydrological stability. Where forests, wetlands, and natural buffers are degraded, female-headed households and marginalized groups are often more exposed to climate shocks (flooding, erosion, pollution) due to land tenure patterns, migration dynamics, and socio-economic constraints [UNFCCC (2022)]. Women are disproportionately affected due to caregiving roles, limited mobility, and exclusion from early warning systems [UN Women (2025)]. Indigenous people are also disproportionately impacted; while they make up only five percent of the world's population, Indigenous people and ethnic minorities are stewards of 80 percent of the remaining biodiversity.

However, women, Indigenous, and vulnerable populations also hold unique knowledge and capacities that can drive inclusive resilience in the face of water-related risks. In Pakistan, women's social networks were key to mobilizing resources and implementing adaptive practices during floods [Gul et al. (2025)]. There is also increasing emphasis on Indigenous knowledges in the Nationally Determined Contributions of countries under the Paris Agreement. Venezuela, for instance, emphasizes leveraging ancestral Indigenous knowledge to develop sustainable technologies, while Guyana highlights that Indigenous culture and traditions promote the sustainable use of nature, as seen in the long-term stewardship of forests and ecosystems on their customary lands [Carmona et al. (2024)].

The removal of natural buffers such as wetlands, forests, and vegetative cover also intensifies the impacts of droughts, and these effects are often exacerbated for women, especially in rural and agri-food sector communities. Women in agrarian economies are disproportionately affected due to their roles in water collection and subsistence farming. Drought conditions can increase the time that women spend each day fetching water by up to 30 percent globally [Carr et al. (2024)]. Climate-driven heat is also shown to reduce children's school performance by four to seven percent annually (Harvard Center for Climate, Health, and the Global Environment, 2025).

These dynamics make it clear that resilience depends not only on physical infrastructure but also on the condition of ecosystems and the inclusion of those most affected. Investing in natural infrastructure—alongside inclusive governance—reduces climate risk for women, Indigenous peoples and other vulnerable groups; accelerates recovery; and supports more sustainable and equitable growth.

Equity by Design: Making Water Systems Work for All

Policymakers and investors today face critical investment decisions in water governance and infrastructure that will shape the future of economies, influencing sustainability and the capacity to respond to shocks such as climate-related hazards, health epidemics, and financial crises. Many key governance and infrastructure challenges can be addressed by optimizing water governance reforms and infrastructure to deliver equitable resilience. Pricing, rights, basin institutions, and nature-based infrastructure solutions should be designed using gender-sensitive and inclusion-aware approaches that protect vulnerable groups and ensure fair distribution of benefits and risks.

In what follows, we list actionable steps to help ensure that water systems not only deliver technical performance but also advance social and economic inclusion, thereby reducing inequality, unlocking productivity, and strengthening resilience for all.

Governance Solutions

• Build Inclusive Water Systems

- Include health cost savings and productivity gains in project cost-benefit analyses. This strengthens the economic case for wastewater treatment upgrades and pollution control measures, especially in vulnerable communities.
- Couple water and sanitation projects with gender-responsive and vulnerability indicators, such as reductions in unpaid care time and school absenteeism.
- Introduce progressive tariff structures and targeted subsidies for low-income and female-headed households. Pair pricing reforms with lifeline water allocations to prevent exclusion while ensuring cost recovery for utilities.
- Promote inclusive policy design by ensuring women and marginalized groups are represented in irrigation committees, tariff-setting processes, catchment management organizations, and benefit-sharing platforms. This can be achieved through quotas, targeted outreach, and capacity-building programs.
- Engage rural women in the design and implementation of water governance reforms to help identify and address unintended consequences, making policies more responsive to their needs and realities.
 - **Example:** In Egypt's 'Sustainable Rural Sanitation Services Program' co-financed by AIIB and the World Bank, local Community Committees and women-only committees at the cluster and village levels help facilitate land donations, raise awareness, secure necessary approvals, and serve as an additional channel for grievance redress.
 - **Example:** Nepal's Sanitation Master Plan mandates gender equity in access to sanitation [UN DESA (2025)].

• Integrate Inclusion in Nature-Based Solutions

- Require participatory planning that includes women, female-headed and low-income households, Indigenous peoples, and landless communities in nature-based solutions such as watershed restoration, wetland protection, and upstream land management projects.

- **Example:** In Ecuador, the “Mujeres Rizomas de Vida School” focuses on mangrove restoration as a nature-based solution by working with women in the country’s coastal communities, incorporating a gender perspective, and adapting to local contexts [UNESCO (2025)].
- **Develop Inclusive Water Pricing Strategies**
 - Assess the distributional impacts of pricing reforms and design policies that promote equitable access. Consider targeted subsidies, tiered pricing structures, or exemptions to ensure that water pricing mechanisms do not exclude or disadvantage vulnerable groups.
 - **Example:** Indonesia’s FINCAPES Project incorporates gender equality into flood-risk modeling and carbon-pricing strategies [Peebles (2024)].
- **Address Land and Water Rights**
 - Strengthen women’s land and water tenure rights to enable their active participation in watershed restoration, payment for ecosystem services schemes, water user associations, and compensation mechanisms. Legal reforms and capacity-building initiatives can help secure tenure and empower women in resource management.
 - **Example:** The Climate Investment Fund’s Forest Investment Program in Mozambique includes women’s forest-related property rights and access, as well as agroforestry training [Climate Investment Funds (2022)].
- **Integrate Inclusive Approaches into Disaster Risk Governance**
 - Involve women and vulnerable populations in planning, decision-making, and implementation of risk reduction strategies. Integrate measures such as mandatory inclusion of women in disaster committees, targeted access to early warning systems, and training programs that build women’s adaptive capacity.
 - **Example:** Gender-sensitive disaster risk reduction policies, including women’s participation in local disaster committees, have been adopted in Viet Nam [Picard (2025)] and Bangladesh [PLAN (2021)].

As climate variability intensifies, traditional water infrastructure systems—often centralized, rigid, and aging—are becoming increasingly unfit for today’s extreme, forcing a reconsideration of

how to design and manage infrastructure [Cosin (2014)]. Climate-related water stress could impose significant economic losses, but investing in adaptive and resilient systems offers a chance to reduce immediate risks while creating long-term benefits.

11.3 The Future of Water Governance: From Risk to Resilience

Unprecedented stressors on the global hydrological cycle are shaping the future of water governance. As climate change accelerates the variability, intensity, and unpredictability of water flows, countries need governance systems capable of managing the full water cycle—from precipitation to runoff, infiltration, storage, use, and return flows. Current governance models, however, remain fragmented, sector-bound, and poorly aligned with the global dynamics of the hydrological system, including its connections to nature. A shift toward an integrated, equitable approach to hydrological and water-cycle governance is essential.

Strengthening Multi-Level Governance

Countries should adopt basin-scale governance frameworks that align decision-making with natural hydrological boundaries rather than administrative ones. Clear mandates for river basin organizations, coupled with transparent data-sharing arrangements between ministries and local authorities, can reduce duplication, improve planning, and create a shared understanding of risks and opportunities. Effective water resilience depends on coherent action across scales. Challenges such as transboundary river management, coastal flooding, groundwater depletion, and climate-driven variability do not align neatly with administrative boundaries. The future, therefore, demands stronger integration across international, national, basin, and local levels.

Globally, water, driven by the shared hydrological cycle, will require more robust cooperation, data exchange, and joint risk-management frameworks. At the national level, coordination among water, agriculture, energy, environment, health, and disaster-management ministries will become increasingly vital as climate shocks spill across sectors. Global and basin-level institutions will play a central role in managing trade-offs and balancing upstream and downstream interests, while

local governments will remain critical for service provision, community resilience, and frontline response. Integrating water governance into national adaptation plans, infrastructure pipelines, and regulatory systems will ensure that investment decisions reflect long-term hydrological realities rather than short-term political or sectoral priorities.

Adaptive Water Management

Adaptive water management is a dynamic approach designed to address the growing uncertainties in water availability, quality, and demand, especially under the pressures of climate change, population growth, and socio-economic shifts. Unlike traditional static management, adaptive strategies emphasize flexibility, learning, and stakeholder engagement to ensure sustainable water use and resilience. Rather than trying to fully shield society from hydrological variability with ever-larger structures, adaptive management expands the range over which the system can function, e.g., demand management in droughts, restoring floodplains and temporary retention areas for floods, and gradually changing crops or allocation rules as conditions shift [Pahl-Wostl (2007)].

Leveraging Data, Technology, and Digital Innovation

Emerging technologies offer transformative potential for water governance. Advanced hydrometeorological systems, earth observation platforms, remote sensing, and digital twins allow for real-time monitoring of water flows, infrastructure performance, and environmental conditions. Artificial intelligence and machine learning can improve flood forecasting, optimize irrigation scheduling, and support predictive maintenance.

The future of water governance will increasingly rely on integrated, open-access data platforms that consolidate information across agencies and ensure open access for planners, regulators, researchers, and communities by enabling transparency, accountability, and informed decision-making. Strengthened information systems will also support participatory governance, empowering communities, civil society, and the private sector to engage meaningfully in planning and oversight.

Resilient Infrastructure: Blending Grey and Green Solutions

As climate variability accelerates, water infrastructure will need to be more resilient, adaptive, and ecologically integrated. Conventional grey infrastructure—dams, reservoirs, levees, and treatment plants—will remain essential but must be complemented by nature-based solutions such as restored wetlands, watershed protection, floodplain reconnection, forest conservation, urban green spaces, and sponge city designs. These approaches not only strengthen the hydrological cycle but often provide higher returns on investment than grey infrastructure alone. Future governance frameworks should prioritize hybrid systems that combine engineered defenses with ecological buffers, enhancing both flexibility and sustainability. This also includes governance arrangements for lifecycle asset management, resilient design standards, circular water approaches, and climate-proofing investments. Governments should mainstream such solutions into national planning, supported by clear standards, financing mechanisms, and monitoring frameworks. Financing strategies—ranging from resilience bonds to blended finance—will be key to upgrading aging infrastructure while expanding coverage in underserved regions.

Ensuring Equity and Social Inclusion

Water risks do not fall evenly. Marginalized communities, informal settlements, rural populations, Indigenous groups, women, and children often bear disproportionate burdens from scarcity, pollution, and excess. Hydrological and water cycle governance must become more equitable and participatory. Communities—especially women, Indigenous groups, and marginalized populations—hold essential knowledge about local water systems and are often the most affected by climate-driven water extremes. Inclusive governance processes and gender-responsive planning strengthen accountability and ensure that policies reflect differentiated vulnerabilities and capacities. Financial mechanisms should also be tailored to support local governments and community-led initiatives that enhance water resilience. Building resilience requires governance systems that actively address inequalities in access, decision-making, and benefit-sharing. Future water governance will need to embed equity as a core

principle: universal access to safe drinking water and sanitation, fair allocation and pricing across sectors, protection of vulnerable groups, and inclusive participation in planning and monitoring. Mechanisms such as community-based management, gender-responsive budgeting, and safeguards against water grabbing and over-extraction will be essential for maintaining trust and social legitimacy.

Aligning Water Governance with Nexus Realities

Water cannot be governed in isolation from the systems it underpins. Food production, energy generation, ecosystem and biodiversity, and public health all depend on water, and decisions in any one domain can create cross-sector impacts. As climate risks intensify, governance systems must increasingly adopt a nexus approach. This means integrated policies that align agricultural water use with food security and climate goals, low-carbon energy transitions with sustainable water withdrawals, and environmental protection with economic development. It also requires institutional mechanisms for coordinated planning, shared information systems, and joint investment strategies across sectors.

Financing a Resilient Water Future

Meeting future water challenges will require substantial and sustained investment—far beyond current levels. Governments will need to mobilize a diverse set of financing instruments: public expenditure, tariffs and cost recovery, private-sector investment, development finance, climate funds, and innovative mechanisms such as insurance schemes and results-based financing. Equally important is governance reform to ensure that financing flows to the most impactful areas: climate adaptation, nature-based solutions, universal service access, and protection of strategic water resources. Transparent and accountable financial governance will be critical for building public confidence and sustaining investment over time.

Role of Multilateral Development Bank and Institutions

Through dialogue, technical assistance, and partnerships, MDBs and development partners at all levels can play a role in enabling inclusive water governance and ensuring that essential services are accessible, affordable, high-quality, and climate resilient. MDBs provide governments with a unique opportunity to allocate capital toward vital, inclusive water investments—covering infrastructure (both nature-based and engineered), institutions, data and regulatory capacity, climate-based policy financing, and mobilizing private sector capital. Through policy support, program design, and targeted measures in projects, MDBs can help prioritize inclusive water governance at the national and local levels, ensuring affordability, quality, climate resilience, and accountability.

MDBs also have a real opportunity to strengthen their impact by leaning more deliberately into the political and social dimensions of water reform. Supporting better water governance means working not only with central ministries, but also with local governments, utilities, civil society organizations, and—critically—women’s groups and other voices that are often excluded from decision-making. These relationships take time to build and require trust, but they are essential for reforms to feel legitimate and to survive long after a project or policy loan has closed. When MDBs invest in inclusive engagement, they help their clients design reforms that are more grounded, more durable, and better aligned with how water is used and managed on the ground.

Taken together, these points suggest a positive reframing of the MDB role. The challenge is not a lack of technical expertise or financial capacity, but a mismatch between the long-term, political nature of water governance and financing models built around concrete contracts and quick results.

By extending time horizons, rewarding governance outcomes, strengthening coordination across sectors, and engaging more deeply with the political

economy of reform, MDBs can become even more effective partners to their clients. Doing so would allow MDB financing to move beyond building infrastructure toward supporting the institutions and incentives that ultimately determine whether water delivers on its promise of equitable, resilient, and sustainable development.

MDBs are diverse, and not all strategies will apply universally. The heterogeneity and complexity of the water sector's private actors must also be carefully considered, from utilities and concessionaires to industrial dischargers and agriculture water users. This includes attention to local stewardship mechanisms (e.g., basin committees, water user associations), customary governance and Indigenous rights frameworks, stakeholder platforms for dialogue, and varied service delivery models (public, private, community-managed, and blended).

11.4 Conclusion: From Managing Crisis to Building Resilience

Effective water and hydrological cycle governance must move beyond reactive crisis management toward proactive, system-wide resilience. Recognizing water as a global common good, governance approaches should integrate both blue and green water flows, address the interconnected risks of scarcity, pollution, and variability, and leverage nature-based solutions alongside technological interventions. Building resilience requires coordinated policies, robust data systems, and inclusive institutions that ensure equitable access, protect ecosystems, and incentivize sustainable use across sectors. By embedding long-term planning, adaptive management, and cross-boundary cooperation, societies can transform water challenges into opportunities for sustainable development, climate adaptation, and shared prosperity.

Box K: Innovative Approaches to Water Law

Recent developments in domestic water legislation highlight a shift toward innovative frameworks that respond more effectively to contemporary water security challenges. Rather than relying solely on traditional command-and-control regulation, countries are adopting more adaptive, integrated, and participatory legal models that align water use with ecological limits and social needs.

Integrated Water Resources Management. One significant trend is the incorporation of Integrated Water Resources Management principles directly into statutory frameworks. This approach aims to balance economic, social, and environmental needs, especially as water becomes more central to energy and food security.

Moving away from the concept of water as property. The trend toward creating market mechanisms for water resource management can be traced back to different concepts of water as either a private property right or a quasi-private usufructuary right [Bosch and Gupta (2023)]. Principled concerns about the commoditization of water aside, there is mounting evidence that treating surface and groundwater as property is inherently dependent on the strength of legal and institutional arrangements to regulate, monitor, and enforce water markets. [O'Donnell, Clark, and Killean (2024)]. In the absence of functioning institutional arrangements, private property rights in water tend to encourage over-exploitation (e.g., Colorado River).

Rights of Rivers. The legal concept of rights of rivers grants rivers, and sometimes their ecosystems, the status of a legal person or entity. This concept represents a legal paradigm shift away from treating nature as a resource to be exploited to further human interests, toward acknowledging rivers as rights-bearing entities with an inherent right to exist, flow, and be healthy [Gilbert et al. (2023)]. It is part of the larger "Rights of Nature" movement, which holds that ecosystems have inalienable rights, just as humans do [Stone (1972)]. In this scenario, wetlands may enjoy legal personhood and would have legal standing. In other words, they would be able to sue and be sued.

While specific rights vary by jurisdiction, some common rights granted to rivers include: (1) the right to flow; (2) the right to be free from pollution; (3) the right to native biodiversity; and (4) the right to regeneration and restoration. The rights of nature approach is informed by the worldviews of Indigenous Peoples, who have long held a spiritual connection to nature and have traditionally regarded rivers and other natural entities as living

Box K. *continued*

beings. There is therefore a close relationship with the relational approach to water (see immediately below). Examples include the Colombian Amazon and other Colombian rivers; the Whanganui River in New Zealand; and the Ganges River and Yamuna River in India. However, this approach is not without its challenges, such as compatibility with the general legal framework (e.g., overall concept of private property) and enforceability, particularly when other powerful economic interests are at stake.

Relationality. The shortcomings of exclusionary rights-centered approaches have led to the development of a relational approach toward water. Such an approach is rooted in longstanding concepts such as water commons and Indigenous law. Cooperative water management at the community level has been successful in diverse locations in managing the sustainable use of water [Ostrom (1990)]. Emphasizing the relationality may provide a solution to the water-as-commodity conundrum as such approach focuses on the interactions and negotiations among multiple actors (e.g., communities and other water users, as well as water entities (e.g., rivers) [Brandshaug (2019)]).

Public participation. Political buy-in and the necessary institutional arrangements are fundamental to the success of both rights-based and relational approaches or any combination of the two [MacPherson et al. (2023)]. Solutions will likely be highly context and location specific. One common element of success identified is devolution to the communal level, including the strengthening of local and Indigenous institutional structures. “[T]he interdependence of rights, obligations, institutions and effective regulation and enforcement” [O’Donnell et al. (2024)] has become increasingly clear.

Together, these innovations demonstrate an important evolution in domestic water law toward more integrated, equitable, and climate-responsive approaches. While their effectiveness varies across contexts, they collectively illustrate a growing recognition that legal systems must evolve in order to safeguard water security amid growing uncertainty.

Box L: How Gendered Labor Distorts Water Governance

Water systems are not neutral—they embed and reproduce inequality. As shown in Chapter 10, undervalued water in agriculture contributes to high virtual water exports from water-stressed, low-income regions. The Chapter shows that the provision of water or the energy used to extract it at very low cost may be politically attractive, especially in agriculture, but it frequently leads to economic distortions and environmental damage. It can also result in social and economic exclusion, because when water prices fail to reflect scarcity, allocation tends to follow power and privilege rather than productivity or need.

Agriculture is often characterized by highly feminized labor forces, raising important distributional considerations for pricing reforms. When pricing reforms ignore gendered wage gaps, rural women, who earn less and dominate agricultural labor, face disproportionate burdens. Limited ability to pay for water reduces household and farm access, undermines cost recovery for utilities, and erodes trust in governance. In agrifood systems, where wage gaps are widest, undervalued water drives high virtual water exports from stressed regions, amplifying vulnerability in feminized supply chains [Benali et al. (2025)]. These inequities distort price signals and weaken the effectiveness of reforms.

At the same time, broken infrastructure forces women to subsidize systemic failure with their bodies, time, and earnings. Hours spent hauling water or waiting for deliveries interrupt paid work, cause income loss, and push girls out of school. Physical strain leads to chronic injuries, while unsafe storage raises health costs. In cities and slums, scarcity creates conditions for gender-based violence: Studies in Chennai found that 90.7 percent of women reported verbal abuse at water points, 18 percent experienced physical abuse, and 8.7 percent reported sexual harassment [Mageswari and Gowtham (2020)].

In slums in Delhi, the lack of infrastructure (toilets, water points) forces women into unsafe spaces, leading to routine fear, harassment, and violence [Chaplin and Kalita (2017)]. In Uganda, as climate change reduces the growing season and rainfall becomes scarce and unpredictable, tensions arise over which crops to grow and prioritize (women mainly grow food crops, while men focus on cash crops) [Nalwanga et al. (2025)]. This can lead to conflict, including domestic violence, especially after poor harvests. Additionally, when food is scarce, women often sacrifice their own nutrition for their families’ well-being.

Box M: Governance of Water Commons for Development—Case Study on the Mediterranean

The Mediterranean is an inland sea shared by advanced and emerging economies. The countries that border it have very different levels of development and different systems for governing water use and preservation. The region is a hotspot of highly interconnected climate risks, with the main economic sectors in the region (agriculture, fisheries, forestry, tourism) being highly vulnerable to climatic hazards, and atmospheric warming rates projected to be 20 percent higher than global average annual rates, and 50 percent warmer in the summer [Ali et al. (2022)].

Outlook for water supply and demand

Climate change is exacerbating water stress caused by poor governance of water resources. All countries in the Mediterranean Basin need to prepare for both a slow-onset rise in water stress and fast-onset crises. Water scarcity already affects 180 million people, and demand could double or triple by 2050.⁹ The population of the Mediterranean Basin is expected to rise from 529 million in 2020 to 611 million by 2050, with one-third living on the northern shore and two-thirds living on the eastern and southern shores. Water supply will fall because of aquifer depletion and climate impacts, including melting glaciers, diminishing and unpredictable rainfall, and sea level rise that causes saltwater intrusion into coastal aquifers. Water flow into the region is also diminishing because of deforestation in Central and West Africa, which disrupts the hydrological cycle that creates the flow of water into the Nile [Gebrehiwot et al. (2018)].

Yearly rainfall is becoming more variable, with increases in dry spells, extreme precipitation, and heatwaves projected by a systematic review of catchment-based studies by Eekhout et al. (2025). This study also foresees negative consequences for other water resources (soil moisture, aquifer recharge, irrigation demand), and for water and soil quality (nutrient concentration, soil salinity, soil erosion). In their most extreme emission scenario, precipitation may decrease by up to 30 to 40 percent over the southern Iberian Peninsula and northwestern Africa by the end of the century.

The decline in freshwater resources is happening both slowly and quickly. In addition to a progressive reduction in rainfall, the gap between water demand and supply could widen suddenly at several points over the next decade.

Higher temperatures are melting the glaciers in the Pyrenees (affecting France and Spain) and the Alps, while snowpack is diminishing in the Moroccan High Atlas mountains (mainly affecting Algeria and Morocco). When this frozen water is gone—for example, mountain glaciers are projected to disappear by 2034 in the Spanish Pyrenees—watersheds in many regions will experience permanent scarcity. Aquifer depletion can also cause sudden drops in the water table. Libya has no permanent rivers and relies for freshwater on a system of mechanical pumping of mainly non-renewable aquifers that has become increasingly unsustainable following the 2011 civil war [Hamad and Saeid (2025)]; intensive pumping has already caused water levels in some aquifers to fall significantly [Closas and Molle (2016)].

Agriculture accounts for more than half of all water withdrawal in most countries around the Basin, with the highest rates at around 87 percent in Morocco, Syria, and Türkiye. In most countries, irrigation is causing more abstraction of water than can be renewed; Libya has the highest rate of unsustainable abstraction, with agricultural water withdrawal at nearly 700 percent of total renewable water resources [FAO (2025)]. Surface flood irrigation is common practice in the Southern Mediterranean, which wastes a large proportion of water through evaporation and runoff. As climate change reduces water availability, food insecurity will increase, with more countries having to rely on imports of virtual water in the form of agricultural products such as wheat.

Governance challenges

Governance is a key challenge. Across the Mediterranean Basin, diminishing water resources will need to be managed at several levels: between users within communities, between countries, and between generations. Within communities, there are traditional methods of governing water commons.

At the inter-state level, over 60 percent of surface water in the southern and eastern Mediterranean is transboundary. All MENA countries draw groundwater from at least one aquifer in common, creating common access issues between states that are likely to worsen as climate change and water scarcity progress [MedECC (2020)].

Box M *continued*

There is also an intertemporal issue of depletion of non-renewable water resources that will deprive future generations of freshwater resources. Glaciers and aquifers are water banks that hold freshwater for very long periods of time. Rising temperatures will melt glaciers faster over the next decade, leaving underground reservoirs as the only climate-proof source of water for future generations.

Fossil aquifers deep in the ground should be the most precious resource because they contain large amounts of water but cannot recharge because they are not connected to surface waters. The water in them has percolated through rock for thousands or millions of years and could be preserved long into the future; yet many are being tapped for use in flood irrigation for agriculture, which causes a large proportion of this fossil water to evaporate.

Governance of aquifers, many of which are transboundary and tapped by users in more than one country, is a key challenge across the region. Even for the renewable groundwater aquifers—those that are connected to surface water—abstraction is massively outpacing the rate of recharge. The rate of abstraction from renewable groundwater resources varies by region and nation (with Libya as the most extreme case), but the southern Mediterranean on average abstracts 24 percent more groundwater than its yearly recharge. Aquifer depletion also causes saltwater intrusion in coastal areas, which is already evident in Catalonia and Sardinia [Mas-Pla et al. (2014)].

Potential for improving the outlook

Improvements in the governance of water as a common resource are possible but will require political leadership. Pricing of water is absent in many rural areas. A proper water price would avoid excessive depletion and help fund capital investment in solutions to water stress. As elsewhere in the world, common access of water users makes it difficult to create institutions based on private property rights or other state interventions to allocate water efficiently. Already a vicious cycle is developing as farmers seek to intensify irrigation to offset the effects of higher temperatures and desertification of their soil to maintain yields. Illegal tapping is accelerating the depletion of aquifers and exacerbating inequality, with those who can afford to drill wells going progressively deeper as the water table drops, leaving smaller farmers without access to groundwater and depleting non-renewable resources.

Technological solutions to counter water scarcity require capital investment, which is available to varying extents around the Mediterranean Basin. Advanced economies can afford to introduce drip-irrigation in agriculture, which is far more efficient than flooding the fields. Desalination can be used to convert seawater into freshwater but remains an energy-intensive process. Over the past decade, the number of desalination plants around the Mediterranean has risen by 90 percent, mainly destined for irrigation [Lafitte and Bellières (2024)]. Desalination plants usually draw power from the national grid, so the energy mix of the country determines the impact on GHG emissions. Renewable energy installation would need to increase significantly around the Mediterranean to avoid desalination causing higher emissions that worsen climate change. In the absence of sound environmental governance, desalination often results in the dumping of brine discharge into the sea, damaging marine ecosystems that local populations rely on for fishing and tourism.

There are other methods of improving water efficiency that would avoid the costs and ecological damage that can result from desalination. Treatment of wastewater for reuse has a much lower energy cost [Hamawand (2023)] than reverse-osmosis desalination plants, which require around three kilowatt-hours per cubic meter of freshwater produced [Kim et al. (2019)]. Better maintenance and upgrading of water infrastructure would prevent a large amount of waste, especially through leaky pipes, with around 25 percent of the water supply lost on average in EU countries, according to a proxy calculation [EurEau (2021)].

Another way to improve efficiency of use is to grade water into drinking quality and lower quality for other uses—such as for cleaning, industrial processes, or irrigation—to reduce unnecessary water treatment. These solutions could be a focus for EU policies in both its member countries and in the MENA region, with an allocation of specific funds to increase water efficiency through better infrastructure and governance, as well as low-energy technological solutions.

^a See UNEP/MAP, <https://www.unep.org/unepmap/resources/factsheets/climate-change>



CHAPTER 12

CONCLUSION

12.1 Where the Water Flows: Building Systemic Water Resilience

The report shows that water cycle functions as critical infrastructure, underpinning agriculture, energy systems, urban resilience, and economic development. The availability of water in the landscape is also critical to sustaining natural capital and biodiversity.

The analyses presented in this report show that the stability of the hydrological cycle can no longer be taken for granted. Rising temperatures, altered moisture circulation, degrading ecosystems, and intensifying extremes are reshaping how water is stored, moved, and transformed. These shifts are already affecting food production, hydropower, urban systems, public health, ecosystems, and national economies. For countries that depend on predictable rainfall, stable seasonal flows, and reliable infrastructure, this moment represents a fundamental turning point.

Across all chapters, the evidence reveals a clear pattern: The hydrological cycle itself is a form of infrastructure, one that crosses borders, sectors, and scales. The global cycle influences local realities, and local land use and governance decisions influence global moisture flows. The productivity of farms, the reliability of hydropower, the safety of cities, and the stability of public finances are downstream of how the cycle behaves and is

governed. Protecting the cycle and ensuring water security are therefore not competing objectives but mutually reinforcing priorities.

The report demonstrates that countries face water risks across four dimensions: too much, too little, too dirty, and too unequal. Floods increasingly carry not only physical damage but major water-quality shocks. Droughts undermine agricultural and urban supply. Pollution burdens fall disproportionately on vulnerable groups. And water stress is now measurably influencing sovereign credit ratings, trade patterns, and food-price volatility. These water risks do not occur in isolation but are shaped by ecosystem conditions, infrastructure design, governance arrangements, social inequities, and the quality of data and forecasting systems. Addressing them demands a shift from fragmented, sectoral responses toward system-wide strategies that align natural, engineered, and institutional systems.

This report demonstrates that infrastructure cannot be treated separately from hydrology, and governance is key to managing this dynamic. Water resilience emerges when these components reinforce one another: when engineered systems are designed to respond to variability, when natural systems stabilize flows and quality, when institutions manage trade-offs transparently, and when economic incentives reflect hydrological realities. Achieving this alignment is both a challenge and an opportunity. It requires rethinking investment

priorities, updating governance structures, strengthening data systems, embedding social inclusion, and mobilizing finance in new ways, including private capital, which will be essential for scaling restoration and resilience solutions.

12.2 Recommendations

Invest Across Water Systems

Climate adaptation means investing across water systems. Water security and infrastructure performance depend on the integrity of these systems. Countries must invest in natural infrastructure that regulates flows and quality, and engineered infrastructure that manages storage, supply and protection.

This includes keeping water in the landscape at multiple levels, which helps secure water for people, livelihoods, health, and ecosystems. Resilient infrastructure depends on these same conditions. At the local level, this involves terraces, soil management, and small-scale storage; at the regional level, wetlands and aquifers that buffer floods and sustain dry season flows; and at the continental level, forest systems that regulate evapotranspiration and moisture recycling. Effective water policy must therefore operate across these nested levels, strengthening local resilience while recognizing regional and global interdependence.

These investments also include restoring forests, wetlands, aquifers and riparian zones; modernizing irrigation networks, hydropower catchments, water supply, and wastewater systems; and building and upgrading stormwater, drainage, and flood-protection assets that can operate effectively amid increasing climatic variability and extremes. They strengthen water security, sustain livelihoods and ecosystems, and reduce stress on infrastructure systems.

Scale Infrastructure for Climate Adaptation

Climate change is intensifying floods, droughts, landslides and sea-level rise, increasing the need for infrastructure dedicated to adaptation to protect vulnerable communities. Many existing assets were designed for historical climate and hydrological

conditions and are increasingly at risk of failure as extremes intensify. Scaling resilient infrastructure for flood protection, drainage, coastal defense, slope stabilization, storage, water supply, and hydropower safety is therefore unavoidable.

To be effective, adaptation infrastructure must be designed to work with a changing hydrological cycle rather than against it. Assets should be planned using forward-looking climate and hydrological scenarios and be integrated with natural systems that buffer extremes and reduce long-term risk.

Reform Water Governance for Tomorrow

Effective governance was identified as a binding constraint throughout the report. As water becomes more variable, governance systems must be able to manage scarcity, coordinate across sectors, mediate trade-offs, and respond quickly to shocks.

Priority actions include aligning allocation rules and planning frameworks and regulatory systems with basin hydrology rather than administrative boundaries; strengthening groundwater management, pollution control, and land use enforcement; integrating water-energy-food-ecosystem trade-offs into national planning and investment decisions; enhancing coordination across ministries, utilities, basin authorities, and levels of government; and improving transboundary cooperation where rivers, aquifers, moisture flows, or wetlands cross borders. Consideration should also be given to addressing the consumption of water-intensive products, including increasing the consumption of less water-intensive foodstuffs, such as alternative proteins.

Governance that is inclusive, transparent, and adaptive allows institutions to respond to changing hydrological realities and enhances the performance of both natural and engineered infrastructure.

Equity and Inclusive Water Systems

The distribution of water risks is deeply unequal. Women, low-income households, informal settlements, Indigenous peoples, and rural communities often bear the greatest burden from scarcity, contamination and infrastructure gaps while having the least influence over water decisions.

Countries and partners should embed gender and social equity assessments into water planning, infrastructure appraisal, pricing policies and basin management; ensure that communities, especially women and Indigenous groups, have meaningful representation in water governance bodies; protect tenure and access rights where nature-based solutions or restoration programs intersect with livelihoods; design social protection mechanisms that reduce the regressive impacts of scarcity and pricing reform; and incorporate health and vulnerability considerations into flood and water-quality risk planning.

Leverage Technology-Enabled Infrastructure

Rapid advances in earth observation, hydrological science, and ecosystem monitoring are transforming our ability to understand how the water cycle functions. Satellite data, remote sensing, and improved modelling now allow governments and investors to measure ecosystem performance, monitor water flows in near real time, and design more effective governance and investment frameworks.

Digital systems are thus now a foundational part of water governance and infrastructure. This report has repeatedly identified data gaps as major constraints, from water quality and groundwater to floods, agricultural water uses, and hydropower operations. Addressing these gaps requires investment not only in digital tools but also in the technology-enabled hard and soft infrastructure that allows water systems to be monitored, managed, and governed effectively.

Countries and MDBs should prioritize hydrometeorological networks that integrate ground, satellite and modelled data; real-time water-quality sensors and early-warning systems; digital twins for basins, utilities, and urban areas; open data platforms that facilitate coordination across sectors

and jurisdictions; and the use of AI and modelling tools for forecasting hydrological extremes and supporting risk-based decision-making. These systems must be embedded within institutions, operational processes, and regulatory frameworks to ensure they translate into better decisions and outcomes.

Stronger digital capacity enhances governance, reduces uncertainty, and enables infrastructure to be operated more safely and efficiently under climatic stress.

Mobilize Finance for Resilience

Water risks are rising while investment in water systems remains insufficient. Addressing these gaps requires mobilizing a broader set of financial instruments and strengthening the enabling conditions for private and blended finance.

Key actions include scaling financing mechanisms such as Payments for Ecosystem Services, Public-Private Partnerships for Nature, nature credits, resilience-linked finance and insurance mechanisms, and policy-based lending instruments; improving the financial viability of utilities and water service providers through cost recovery, predictable regulation, and lifecycle asset management; incorporating water-risk assessments into sovereign, sub-sovereign, and sectoral financial planning; aligning fiscal and subsidy policies with water conservation and long-term resilience objectives; and directing public finance toward investments that leverage or catalyze private capital where appropriate. Financing approaches must reflect the long-term dynamics of the hydrological cycle and support investments that build resilience rather than compound risk.

Together, the world needs to turn the water crisis into water opportunities and transform water bankruptcy into water bankability.





APPENDICES

Appendix 1: Data and Estimations for Chapter 5

Study Design

An 'ex-post' evaluation is designed using a cross-sectional comparison between the beneficiary and non-beneficiary water user groups (WUGs) to determine the impact of irrigation infrastructure rehabilitation undertaken within the SIMURP in three regions (West Java, Nusa Tenggara, and South Sumatra) of Indonesia.

Treatment Group: The treatment groups for West Java and Nusa Tenggara are selected at random from a pre-existing list of beneficiary WUGs. However, since the rehabilitated structure was concentrated within a small geographical region in Sumatra, all the WUGs formed the treatment group. In West Java and Nusa Tenggara, canals that rely on traditional surface-water irrigation are rehabilitated, while in Sumatra, canals attached to a tidal irrigation system are rehabilitated. The treatment groups in West Java, Nusa Tenggara, and Sumatra consist of 450, 348, and 350 household observations collected from 45, 29, and 10 WUGs, respectively.

Comparison Group: The comparison group is chosen in a stepwise manner. In the first step, a list of comparison villages was developed for

each region in close collaboration with SIMURP's Project Management Unit. These were villages and WUGs with similar production systems as the treatment WUGs, which were not part of the SIMURP beneficiary lists and did not receive any spillover benefits from the project. In the second step, these comparison villages were validated by field survey teams to ensure comparability in terms of commodities produced and their irrigation systems. The comparison groups in West Java, Nusa Tenggara, and Sumatra consist of 449, 372, and 349 household observations collected from 45, 31, and 10 WUGs, respectively.

Empirical Strategy

In the case of cross-sectional data, without credible instrumental variables, the IPWRA method proposed by Wooldridge (2010) provides a credible way of estimating the impact of interventions on outcome variables. The identification is based on the conditional independence assumption, which assumes that after controlling for observables that explain selection into treatment, the treatment assignment is independent of potential outcomes. A set of covariates was included to ensure good overlap between treatment and comparison households, satisfying the conditional independence assumption. While conditioning on a rich set of observable covariates may help to reduce selection bias due to unobservables [Imbens and Wooldridge

(2009)], the threat from unobserved heterogeneity remains. Therefore, the results should be interpreted as suggestive but not conclusive of causal effects.

IPWRA estimation follows a three-step process. The first step estimates a logit regression of matching variables to obtain the inverse probability weights for each treatment arm. The selection of covariates is based on previous studies related to irrigation and household well-being. These covariates include household demographics, characteristics of the household head, weather variables from satellite data, and land ownership.

In the second step, a weighted linear regression is estimated separately for the treatment and comparison groups, where weights are based on the inverse probability weights calculated in the first step. In the third and final step, the IPWRA computes the average predicted outcomes for comparison and treatment groups using the generalized propensity scores and the conditional means estimated in the first two steps. The estimates in the second step are obtained through weighted least squares, represented as:

$$y_{hj} = \alpha + \phi X_{hj} + \mu_j + \varepsilon_{hj} \quad \forall \text{treat} \in [0,1] \quad (1)$$

where y_{hj} is the outcome of interest for household h in subdistrict j . X_{hj} are the set of covariates as described above. μ_j are subdistrict fixed effects that control for time-invariant, unobserved subdistrict-level characteristics that could be correlated with outcomes, and ε_{hj} are independent and identically distributed errors across subdistricts and households.

Then in the third step, the difference of the predicted outcome means from Eq (1) for $\text{treat} = 1$ and $\text{treat} = 0$ is estimated, producing the average treatment effects (ATE) of the beneficiary group.

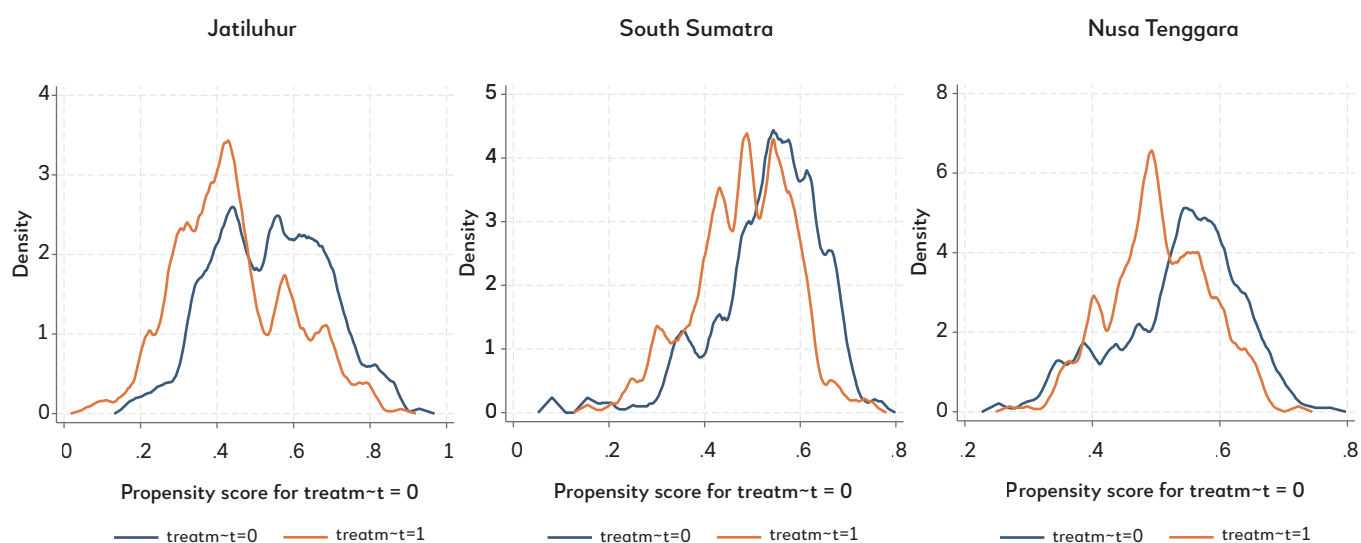
$$ATE_{IPWRA} = n^{-1} \sum_{h=1}^n w_h [r_T(X, \delta_T) - r_C(X, \delta_C)] \quad (2)$$

where ATE_{IPWRA} are the intent-to-treat (ITT) effects for the irrigation treatment, estimated separately for West Java, Nusa Tenggara, and South Sumatra, respectively. The ITT is the measure of the impact of the project on all households that potentially benefited from the project. Since the benefits accrued to all participants could differ based on their participation in the project and their proximity and access to the infrastructure, the ATE from the IPWRA estimation provides us with the ITT effects. In Eq 2, n is the number of observations, w_h is the inverse probability weight for each observation h , while $r_i(X)$ describes the regression model for beneficiary (T) and comparison group (C) with covariates X and estimated parameters δ_i , where δ_i are obtained from weighted regression procedures.

The estimation procedure is completed by bootstrapping the entire process 750 times since most of the regressions do not converge with the standard *teffects* package in Stata. For each bootstrap iteration, the standard errors are clustered at the subregion level to account for intra-cluster correlation in error terms.

An important assumption for identifying the impacts is the strict overlap assumption, which asserts that conditional probabilities are bounded away from zero and one. The overlap in propensity scores is verified through the graphs reported in Figure 40 which reports the kernel density of the probabilities of being in any group, after reweighting. No spikes are detected at the extremes of the distributions, meaning that all observations have a positive probability of being in each group. Finally, normalized differences were calculated for each covariate in each region and check their balance, as proposed by Imbens and Wooldridge (2009) (Table 12).

Figure 40: Propensity Scores Overlap



Source: AIBB staff estimates.

Table 12: Normalized Differences Among Covariates Between Beneficiaries and Non-Beneficiaries After the IPW Stage

West Java	Normalized Difference Score	Nusa Tenggara	Normalized Difference Score
Owned land area (ha)	-0.17818	Household head gender	-0.00119
Total number of household members	-0.00291	Household head age	-0.00802
HH head gender	-0.01089	Total HH members	0.00591
HH head age	0.030503	Owned land area (ha)	0.001834
HH Occupation (full time farmer)	-0.00235	Minimum precipitation over the year	0.014125
HH Occupation (part time farmer)	-0.0017	Maximum precipitation over the year	-0.00193
Total number of months lacking rainfall	0.011207	Average temperature over the year	-0.00351
Primary education	0.020433	Primary education	-0.0022523
Secondary education	0.019651	Secondary education	-0.0000262
Tertiary education	-0.09892	Tertiary education	0.0031127

South Sumatra	Control
HH gender	-0.05285
HH age	-0.09835
Owned land area (ha)	-0.04005
Average precipitation over the year	0.020108
Average temperature over the year	-0.00928
Primary education	-0.00034
Secondary education	-0.00425
Tertiary education	0.000165

Notes: ha = hectare.

Source: AIBB staff estimates.

Appendix 2: Data and Estimations for Chapter 6

Event time is centered on the week of flood onset, and an event window is constructed to span several weeks before and after each event. This facilitates the examination of pre-event trends (important for assessing identification validity) and the dynamic evolution of pollution peaks and recovery trajectories following a flood. To isolate these dynamic responses from confounding factors, station fixed effects are included to absorb all time-invariant local characteristics such as geography, long-term land cover, and monitoring instrumentation. Country-by-week fixed effects are also included to account for broader temporal variation, including seasonal patterns, regional hydrological conditions, and changes in monitoring practices. Together, this event-centered design and fixed-effects structure enable a clean identification of how water quality indicators behave before, during, and long after flood events. The event-study specification is given as

$$Y_{icd} = \alpha + \sum_{k \in K, k \neq -1} \beta_k \cdot \mathbf{1}\{\tau_{id} = k\} + \gamma_i + \rho_d + \theta_f + \varepsilon_{icd}$$

where Y_{icd} denotes the average concentrations of different water-quality indicators c (to be elaborated later) at station i during week d , measured in logarithmic form. In practice, the regressions are implemented for each water quality indicator separately. γ_i and ρ_d are station fixed effects and country-by-week fixed effects, respectively. The flood event fixed effects θ_f control for heterogeneity in flood characteristics, thereby enabling the identification of within-event temporal dynamics. Standard errors are clustered at the station level to account for serial correlation. The coefficient β captures the average treatment effect of floods in event time. $\tau_{id} = d - T_i$ represents the number of weeks relative to flood onset, where d and T_i refers to the calendar week and the event week, respectively, with $k = -1$ serving as the reference

period. The specification includes eight-week leads and lags to capture pre-event trends and post-event recovery trajectories. The β_i coefficients thus measure deviations in pollutant concentrations from pre-flood conditions, capturing the magnitude, persistence, and speed of system responses to shocks—dimensions recognized as core components of environmental resilience [Folke et al. (2010)].

To examine whether upstream land-use composition modulates flood-induced water-quality responses, the baseline specification is extended to incorporate different dominant land-use types. Each monitoring station is classified by its predominant land-use category, defined as the land type that represents the largest share of upstream grid cells. In practice, stations are categorized as urban-dominated, agriculture-dominated, or forest-dominated if the respective land type accounts for more than 50 percent of upstream grid cells within the station's catchment. The heterogeneous-effects specification is estimated separately for each land-use category and each water quality indicator using

$$Y_{icd} = \alpha + \sum_{k \in K, k \neq -1} \pi_k \cdot \mathbf{1}\{\tau_{id} = k\} \cdot Landuse_i + \sum_{k \in K, k \neq -1} \beta_k \cdot \mathbf{1}\{\tau_{id} = k\} + \gamma_i + \rho_d + \theta_f + \varepsilon_{icd}$$

where $Landuse_i$ is a dummy variable that denotes the dominant land-use type at station i . The coefficients π_k capture the heterogeneous impacts of land-use composition on the flood-water-quality relationship at each event time. Restricting the analysis to stations where a single land-use type dominates (>50 percent threshold) ensures that estimated effects reflect genuine differences in land-use function rather than compositional ambiguity. All other parameters follow the same definitions as in the baseline specification. Results are estimated separately for urban-dominated, agriculture-dominated, and forest-dominated stations.

Appendix 3: Data and Estimations for Chapter 7

The study uses the quasi-random spatial rollout of a Ramsar designation to identify the effect of the designation on wetland health outcomes in a canonical TWFE model as:

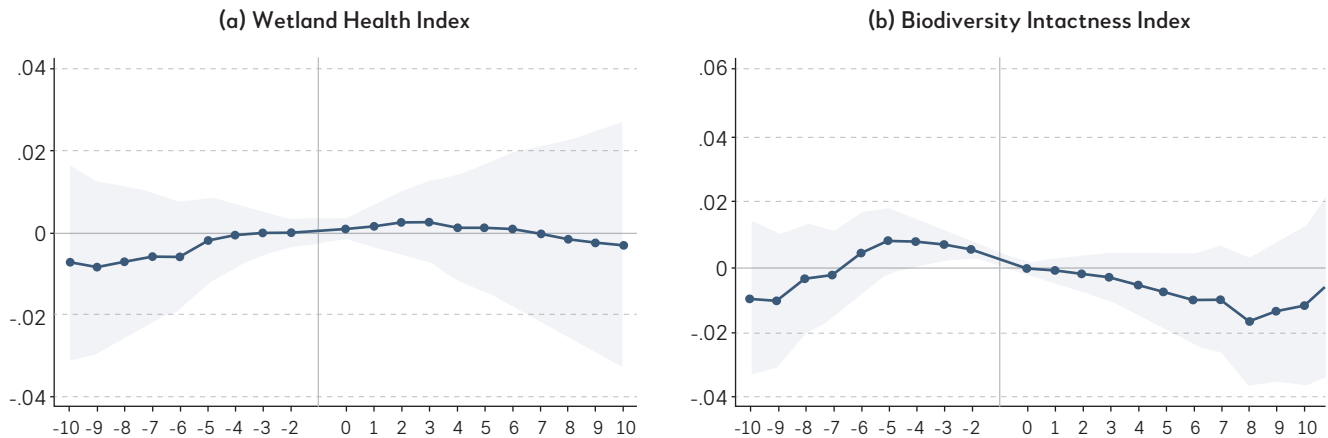
$$y_{icst} = \alpha + \beta T_{icst} + \gamma X_{icst} + \mu_{icst} + e_{icst}$$

where y_{icst} are wetland health outcomes (e.g., WHI, BII, water extent, vegetation and forest area, and urban and agricultural land cover) for each site i , in country c , of wetland type s , and time t . X_{icst} are control variables including weather variables in each of the sites (e.g., precipitation, humidity, and temperature), and country-level variables such as EPI and WGI.

μ_{icst} are a rich set of fixed effects, including site-level fixed effects, wetland type fixed effects, country fixed effects and time fixed effects. Site fixed effects allow us to control for time-invariant unobserved characteristics of each site, while wetland-type fixed effects control for time-invariant unobservables associated with inland, coastal, and man-made wetlands. Time fixed effects control for time variant heterogeneity.

β captures the differential impact of a Ramsar designation under the standard “parallel trends” and “no anticipation” assumptions. Indeed, Figure 41 shows no prior differential trends before the treatment. The baseline model was also extended to the heterogeneous treatment effects case using the ‘doubly-robust’ Callaway and Sant’Anna (2021) estimator to avoid bias arising from imposing a homogeneous treatment effect when treatment timing is staggered.

Figure 41: Event Study Plot of a Ramsar Designation on WHI and BII



Source: AIB staff estimates.

Appendix 4: Data and Estimations for Chapter 8

Outcomes

The primary outcome variable in this analysis is the capacity factor, an indicator of hydropower generation efficiency. It is defined as the ratio of actual electricity produced to the theoretical maximum output, calculated as installed capacity multiplied by operational time.

$$\text{Capacity Factor (CF)} = \frac{\text{Annual Generation (MWh)}}{\text{Installed Capacity (MW)} \times \text{Hours in Year}}$$

Here, *Annual Generation* is the actual energy produced in a year, *Installed Capacity* is the plant's installed capacity, which may vary over time, and *Hours in Year* are usually 8,760 and are adjusted to 8,784 for leap years.

This ratio gives a value between 0 and 1 (or 0–100 percent), indicating the proportion of time the plant effectively generates power at its full capacity. Plants with CF close to 1 operate near maximum capacity most of the time, while lower CF values suggest underutilization or variability in water availability.

Annual plant-level capacity factors were computed by AIIB staff. The plant-level annual electricity generation data for the United States comes from the EHA Existing Hydropower Assets Net Generation Plant Database (2003–2023) and EHA Capacity Plant Database (2005–2024). Data for Argentina and Australia come from CAMMESA (Compañía Administradora del Mercado Mayorista Eléctrico Sociedad Anónima) and National Greenhouse and Energy Reporting, respectively.

Key Independent Variable

The key explanatory variable is the leaf area index (LAI), measured within each reservoir's upstream catchment. To identify the upstream catchment area for each reservoir, the HydroBASIN dataset—a globally vectorized hydrographic database of river basins is used. The delineation process first identified the sub-basin in which each reservoir is located, and then traced all sub-basins that drain into it directly or indirectly, based on river network topology. The aggregation of these connected sub-basins defines the reservoir's total upstream catchment area.

The LAI is a widely recognized biophysical indicator representing the total one-sided leaf area per unit ground of surface area and serving as a proxy for vegetation density. The Global Land Surface Satellite Leaf Area Index (GLASS LAI) products, produced by the Geography Department at the University of Hong Kong, were used to construct a consistent LAI panel dataset. The mean LAI value was then calculated for each catchment and each year, capturing interannual variations in upstream vegetation cover. This approach ensures both temporal consistency and spatial comparability across study sites.

Control

- Runoff flows were derived primarily from the Global Flood Awareness System (GloFAS). GloFAS provides gridded daily discharge data generated through a semi-regulated hydrological model that incorporates major dams and lakes using expert-based parameters. Developed jointly by the European Commission and the European Centre for Medium-Range Weather Forecasts under the Copernicus Programme, GloFAS is calibrated against nearly 2,500 river gauging stations worldwide, demonstrating particularly high performance across large parts of North and South America. Based on reservoir locations, daily runoff data were extracted and aggregated to monthly and annual inflow values.
- Sediment data were obtained from the global sediment database (GSED), a satellite-derived resource that provides the most comprehensive global record of fluvial suspended sediment concentration (SSC) from 1985 to 2020 [Sun et al. (2025)]. GSED applies a multi-band ratio weighted algorithm to convert Landsat-4/5/7 surface reflectance data into SSC estimates, which were validated using concurrent in site-level observations from multiple agencies, including GEMStat, USGS, the Mekong River Commission (MRC), HYBAM, and Environment Canada. For each reservoir, the nearest GSED river reach within its upstream catchment was identified and monthly SSC data were extracted. GSED records show substantial data gaps during the Northern Hemisphere winter (December–February), likely due to periods of river ice cover. To address this, long-term GloFAS discharge data (1981–2024) were used to derive the monthly mean flow for each station and identify the flood season (six consecutive months with the

highest cumulative discharge). Monthly sediment inflow was then calculated as SSC multiplied by runoff, and flood season sediment inflow was computed by aggregating monthly data following imputation where necessary.

- Climate factors come from the CRU TS v4.09 dataset. This dataset was initially developed by Harris et al. (2020) which provided consistent gridded meteorological time series by interpolating quality-controlled weather station observations. For each catchment, annual averages of land-surface temperature, precipitation, and potential evapotranspiration were calculated.
- Plant-level characteristics—including plant type and reservoir details—were obtained from GloHydroRes [Shah et al. (2025)], a harmonized, georeferenced dataset that consolidates multiple open-source inventories of global hydropower plants and reservoirs. GloHydroRes covers 7,775 hydropower plants worldwide, representing approximately 80 percent of globally installed hydropower capacity, making it essential for cross-country comparative analysis.

Appendix 5: Data and Estimations for Chapter 9

Table 13: List of Countries

ISO	Country	Income Group	ISO	Country	Income Group
ARG	Argentina	UMIC	JOR	Jordan	UMIC
ARM	Armenia	UMIC	JPN	Japan	HIC
AUS	Australia	HIC	KAZ	Kazakhstan	UMIC
AUT	Austria	HIC	KOR	Republic of Korea	HIC
AZE	Azerbaijan	UMIC	LBN	Lebanon	UMIC
BEL	Belgium	HIC	LKA	Sri Lanka	LMIC
BGR	Bulgaria	HIC	LTU	Lithuania	HIC
BHR	Bahrain	HIC	LUX	Luxembourg	HIC
BIH	Bosnia and Herzegovina	UMIC	LVA	Latvia	HIC
BLR	Belarus	UMIC	MAR	Morocco	LMIC
BLZ	Belize	UMIC	MEX	Mexico	UMIC
BOL	Bolivia	LMIC	MKD	North Macedonia	UMIC
BRA	Brazil	UMIC	MLT	Malta	HIC
BRB	Barbados	HIC	MNG	Mongolia	LMIC
CAN	Canada	HIC	MYS	Malaysia	UMIC
CHE	Switzerland	HIC	NGA	Nigeria	LMIC
CHL	Chile	HIC	NLD	Netherlands	HIC
CHN	China	UMIC	NOR	Norway	HIC
COL	Colombia	UMIC	NZL	New Zealand	HIC
CPV	Cabo Verde	LMIC	PAK	Pakistan	LMIC
CRI	Costa Rica	UMIC	PAN	Panama	UMIC
CYP	Cyprus	HIC	PER	Peru	UMIC
CZE	Czechia	HIC	POL	Poland	HIC
DEU	Germany	HIC	PRT	Portugal	HIC
DNK	Denmark	HIC	PRY	Paraguay	UMIC
DOM	Dominican Republic	UMIC	ROU	Romania	UMIC
ECU	Ecuador	UMIC	RUS	Russian Federation	UMIC
EGY	Egypt	LMIC	SAU	Saudi Arabia	HIC
ESP	Spain	HIC	SGP	Singapore	HIC
EST	Estonia	HIC	SLV	El Salvador	LMIC
FIN	Finland	HIC	SRB	Serbia	UMIC
FJI	Fiji	UMIC	SUR	Suriname	UMIC
FRA	France	HIC	SVK	Slovakia	HIC
GBR	United Kingdom	HIC	SVN	Slovenia	HIC
GEO	Georgia	UMIC	SWE	Sweden	HIC
GRC	Greece	HIC	THA	Thailand	UMIC
HND	Honduras	LMIC	TTO	Trinidad and Tobago	HIC
HRV	Croatia	HIC	TUN	Tunisia	LMIC
HUN	Hungary	HIC	TUR	Türkiye	UMIC
IDN	Indonesia	LMIC	UKR	Ukraine	LMIC

continued on next page

Table 13 *continued*

ISO	Country	Income Group	ISO	Country	Income Group
IRL	Ireland	HIC	USA	United States of America	HIC
ISL	Iceland	HIC	VEN	Venezuela	UMIC
ISR	Israel	HIC	VNM	Viet Nam	LMIC
ITA	Italy	HIC	ZAF	South Africa	UMIC
JAM	Jamaica	UMIC			

Source: Income groupings are based on World Bank Group income classifications.

Table 14: Environmental Stress Indicator (EPI)

	(1) All	(2) HIC	(3) UMIC	(4) LMIC
EPI	-0.0625*** (0.0226)	-0.0305 (0.0361)	-0.0772** (0.0278)	-0.0927 (0.1081)
Macro-Financial Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Observations	1,532	802	507	206
Number of Countries	71	37	23	10

Source: AIB staff estimates.

It could be that our results in Table 6-Table 9 highlight environmental issues correlated with water stress rather than water stress itself. To investigate this, a proxy for environmental stress is taken as a placebo test to see whether it returns results consistent with the study's main findings. Water stress is therefore replaced as the independent variable of interest with Yale University's Environmental Performance Index (EPI) [Block et al. (2024)]. All variables in the EPI with a weight of two percent or larger are retrieved to compute a re-weighted average of the 22 indicators for each country-year combination. This creates a new index that incorporates around 76 percent of the original EPI. Replacing water stress with this weighted average EPI score yields the results in Table 14. OLS fixed effects panel regressions are run for each country group, aligning with column (1) of the main results tables.

The table shows that the main coefficient, which refers to the effect of EPI on credit ratings, is unsurprisingly larger than the equivalent regressions for water stress. Since environmental stress is a broader term than water stress, any effect would be expected to be of a greater magnitude to capture the more pronounced effect on credit ratings. While the coefficient for the lower-middle-income country group sample (column (4)) is similar to the ones in Table 9, it is statistically insignificant, meaning that the effect cannot be adequately determined. This highlights how the study's estimated impact on credit ratings is unique to water stress and not some other variable.

Appendix 6: Data and Estimations for Chapter 10

Deriving Aggregate and Bilateral VWT Balance

First, an NM by NM multi-region IO table is assembled, where N represents 62 countries and M represents the three aggregated sectors (agriculture, industry, and services).³⁵ Following the literature

$$\mathbf{VW} = \boldsymbol{\omega}(\mathbf{1} - \mathbf{A})^{-1}\mathbf{Y}$$

where \mathbf{VW} is the matrix of virtual water flows between countries, $\boldsymbol{\omega}$ the diagonal matrix of water use efficiency defined by the ratio of country-sector water withdrawals and country-sector output, \mathbf{A} is the standard production matrix derived from the MRIO with $(\mathbf{1} - \mathbf{A})^{-1}$ as the Leontief inverse, and \mathbf{Y} is a diagonal matrix representing the final demand of each country-sector. The above equation provides for the decomposition into domestically sourced or imported components, similar to a global value chain analysis [Koopman et al. (2014); Casella et al. (2019)].

The i^{th} column of \mathbf{VW} shows the source of virtual water embedded in country i . Take country 1: The sum of column 1 thus provides for the total water use, from its own sources or virtual water imported, in service of its final demand, consisting of both consumption and export of final goods. With this, the net virtual water balance of i is given as

$$NVW_i = \sum_s \left[\sum_{j=1}^N vw_{ij,s} - \sum_{j=1}^N vw_{ji,s} \right]$$

which is essentially the sum of rows less the sum of columns aggregated across all three sectors denoted by s . The bilateral net virtual water trade balance between any two countries i and j can also be derived as

$$NVW_{ij} = \sum_s vw_{ij,s} - \sum_s vw_{ji,s}$$

where $vw_{ij,s}$ is the virtual water import of j from i in sector s and $vw_{ji,s}$ is the import of i from j . Note that by definition, $NVW_{ij} = -NVW_{ji}$.

Deriving Relative Water Abundance

The analysis follows the methodology of Kang et al. (2007) to derive a Euclidean distance-based measure of factor abundance and applies it to a high-dimensional analysis with five factors: water (W), physical capital (K), high-skilled labor (H), semi and low-skilled labor (L) and arable land (F). The relative abundance of water is given as

$$d_{wi} = \left[\left(\frac{K_i/K_G}{W_i/W_G} \right)^2 + \left(\frac{L_i/L_G}{W_i/W_G} \right)^2 + \left(\frac{H_i/H_G}{W_i/W_G} \right)^2 + \left(\frac{F_i/F_G}{W_i/W_G} \right)^2 \right]^{\frac{1}{2}} \mathbf{V}i$$

Consider the first term within square brackets—it is the ratio of country i capital stock K_i relative to global average per country capital stock K_G , divided by the ratio of water endowment A_i and global average per country water endowment A_G . This whole term thus gives the abundance of capital, relative to the abundance of water. With many factors, d_{wi} provides a Euclidean distance-based measure of abundance. Computed across all countries, d_{wi} provides the ranking of water abundance, relative to all other factors.

Gravity Equation for Factor Content

Following Anderson and van Wincoop (2004) for a one sector model, and putting aside the need to consider the general equilibrium effects of multilateral resistance (which will be justified subsequently), the exports of i to j is given as

$$X_{ij} = \left(\frac{p_{ij}^{1-\sigma}}{P_j^{1-\sigma}} \right) E_j$$

where p_{ij} is the price of export presented by i to j (inclusive of trade cost), $P_j = \left(\sum_{i=1}^N p_{ij}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}$ is the constant elasticity of substitution price aggregator across the prices presented by all countries including itself and E_j the expenditure in market j . Using a bar to denote the relevant variables for the one sector model, water factor used for X_{ij} can be estimated by multiplying $\bar{\omega}_i$ (which measures the water content in i per unit output) to derive the water factor content in export

³⁵ While the MRIO has greater granularity in terms of sectors, water withdrawal data is only available at the three-sector level. Hence, the finer sectoral input out data of the MRIO is aggregated to the three broader sectors to match with water withdrawal data.

$$\overline{vw}_{ij} = \overline{\omega}_i X_{ij} = \overline{\omega}_i \left(\frac{p_{ij}^{1-\sigma}}{p_j^{1-\sigma}} \right) E_j$$

where $\overline{\omega}_i$ is related to the diagonal matrix ω introduced in Equation 1. In a one-sector aggregated model, $\overline{\omega}_i$ can be taken as the combined use for all three sectors. The analysis models the price of a unit good as $p_{ij} = c_{ij} t_{ij}$, which consists of two components: The cost of good c_{ij} and iceberg trade cost t_{ij} . It further models output as a Cobb-Douglas production function $Y_{ij} = (\gamma_i \omega_i)^\alpha o_i^{1-\alpha}$ where γ_i is the water-augmenting productivity factor, $\overline{\omega}_i$ is the water inputs, and o_i represents all other inputs.

With perfect competition, $c_{ij} = \theta_i (\gamma_i^{-1}) p(\omega_i)^\alpha p(o_i)^{1-\alpha}$ where $p(\omega_i)$ is the tariff of water and $p(o_i)$ the cost of all other intermediate inputs (including imported intermediates) entering into production, θ_i the standard function reflecting the cost constant—this is inversely related to water productivity γ_i . Given standard cost shares $\overline{\omega}_i p(\omega_i) = \alpha c_{ij}$, water use $\overline{\omega}_i = \frac{\alpha c_{ij}}{p(\omega_i)}$ is inversely related to water tariffs. With these assumptions, the factor export equation becomes

$$\overline{vw}_{ij} = [\theta_i (\gamma_i^{-1})]^{2-\sigma} p(\omega_i)^{\alpha(2-\sigma)-1} p(o_i)^{(1-\alpha)(2-\sigma)} t_{ij}^{1-\sigma} p_j^{\sigma-1} E_j$$

Following Thia and Ong Lopez (2023), one can take the ratio of exports and by assuming symmetry in bilateral trade costs ($t_{ij} = t_{ji}$), the ratio can be expressed as $\frac{\overline{vw}_{ij}}{\overline{vw}_{ji}}$. Note that a ratio greater than 1 would indicate a trade surplus for country i , while a ratio below 1 would indicate a deficit. Taking logs of ratio results in a regression equation that can be implemented

$$\begin{aligned} \log(\overline{vw}_{ij}) - \log(\overline{vw}_{ji}) &= d_i + d_j + (2 - \sigma) \log(\theta_i) \\ &\quad - (2 - \sigma) \log(\theta_j) + \log(E_j) \\ &\quad - \log(E_i) + [\alpha(2 - \sigma) - 1] \\ &\quad [\log p(\omega_i) - \log p(\omega_j)] \end{aligned}$$

This provides a simplified way of estimating how water tariff differences captured by $\log p(\omega_i) - \log p(\omega_j)$ affect bilateral net virtual water balance, where log expenditures control for effects of market sizes, and exporter fixed effects (d_i) and importer fixed effects (d_j) absorb the other variables specific to i and j , respectively. Essentially, the model is a significant simplification that sidesteps many issues, including the role of trade costs, trade resistance, and other input costs, by assuming these are either cancelled by assumption of symmetry or captured by fixed effects.

The above identification depends on all countries using the same aggregate technology set embedded in the cost function, but it allows countries to have different relative input prices and hence to produce at different points on the same cost curve. The identification strategy also rests on the assumption that factor intensity is the same for country i regardless of where it sells its products. Similarly, the conditions in the import market j is the same for all i exporting countries.

These allow the analysis to focus on the role of water tariffs and their elasticity on virtual water trade. The tariff elasticity of virtual water exports $\alpha(2 - \sigma) - 1$ reflects the interaction of two factors, the elasticity of substitution of the underlying good (σ) and the cost share (α), where a lower cost share leads to a lower elasticity. These also govern the extensive and intensive margins, respectively. Note that if water is the only input ($\alpha = 1$) and hence there is no possibility of substitution to other inputs, the price elasticity term collapses to the familiar $(1 - \sigma)$ as per the standard constant elasticity of substitution model.



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ASIAN INFRASTRUCTURE FINANCE 2026

WHERE THE WATER FLOWS

Infrastructure and Governance for a Sustainable Water Cycle

Water underpins biodiversity and ecological resilience, economic performance, and social stability, and yet it is rarely managed as the interconnected system it is. At the global scale, water is a holistic system, flowing through the atmosphere, soils, rivers, wetlands, aquifers, and glaciers. At a regional level, water is transboundary, with microclimates and any associated disruptions affecting whole regions. Water is also a local issue, where the availability of water often exerts a strong impact on livelihoods. Economic activity, on the other hand, puts pressure on local and regional water systems. Climate change is now destabilizing this hydrological cycle. These shifts will have profound regional and local impacts.

This report, *Where the Water Flows*, is of direct relevance to government ministries, planning agencies, and multilateral development banks: The hydrological cycle itself functions as infrastructure. It delivers essential services on which economies depend, including flow regulation, storage, water supply, energy generation, food production, and risk reduction. The first key message of the report is that the water cycle, itself a key infrastructure for humanity, must be protected through investments in nature and landscape conservation. The report is also about adaptation and water resilience, and how water-related infrastructure investments and governance reforms can achieve this. The findings of this report point to a strategic shift away from fragmented water responses toward systemic water resilience.