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TECHNICAL REPORT

Climate Resilient Water Infrastructures for Sustainable Food, Land and Water Systems in India

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CGIAR Climate Action Program

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Front cover photo: A minor irrigation structure in Paschim Medinipur, West Bengal. (*photo:* Tanmoy Bhaduri/IWMI)
Back cover photo: A water recharge structure created to store rainwater and provide irrigation to farm in Parschim Medinipur, West Bengal (*photo:* Tanmoy Bhaduri/IWMI)

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1. Introduction

The water sector in the Global South is facing increased variability and unpredictability because of climate change. It is intensifying the water risks as witnessed in increased frequency and severity of droughts, floods, and amplified water scarcity, threatening livelihoods—particularly in agriculture-dependent communities and economies. Risks are further compounded by inadequate water storages, old & aging water infrastructures including water storage, conveyance and distribution, low water use efficiencies across water use sectors, increasing water demand and insufficient integration of climate change and resilience into water management systems. It’s also highlighted in the IPCC's Sixth Assessment Report. Reduced agricultural yields, declining groundwater tables, increased evaporative demand and growing uncertainty in rainfall patterns are compounding vulnerabilities and limiting the adaptive capacity of smallholder farmers, especially women and marginalized groups. As countries in the Global South grapple with the twin challenges of climate change and water scarcity, climate resilient water infrastructures and management offer a unique entry point for sustainable agri-food systems under growing climate risks.

The year 2024 recorded a global average temperature of 15.10°C- meaning 0.12°C higher than the previous highest global average temperature in 2023 (https://climate.copernicus.eu). This was 1.60°C warmer than the temperature levels of pre-industrial time which means it was the first calendar year when temperatures exceeded 1.5 °C (the level set by the Paris Agreement). Widespread floodings were seen in many places in the year 2025 also.

A warm climate drives many natural catastrophes. In 2024, severe floods hit Europe and the UAE and resulted in estimated insured losses of close to USD 13 billion. Since flood damages can’t be fully controlled, society has to learn to live with floods. In any case, resilient infrastructures are helpful in the meaningful control of floods. Swiss Re estimates show the total economic and insured losses in 2024 at 328 and 146 billion USD (2024 prices) (Swiss Re, 2025). As climate change intensifies extreme weather events, losses are expected to rise, more so in urban sprawls. Swiss Re also suggests that adaptation is the key and protective measures, such as dykes, dams and flood gates, are up to ten times more cost-effective than rebuilding.

This unprecedented rise of temperature also means changes in precipitation patterns and growing frequency and intensity of extreme events such as floods and droughts. IPCC (2021) have noted that “the frequency and intensity of heavy precipitation events have increased since the 1950s over most land areas for which observational data are sufficient for trend analysis, and human-induced climate change is likely the main driver”. They also conclude that increases in agricultural and ecological droughts in some regions can be attributed to increased evapotranspiration from land areas, caused by human-induced climate change.

The scope of this report is to provide a brief review of the concept of resilient water infrastructures and water management and describe the current status and future work needed on this important subject in India.

1.1 What is Water Infrastructure?

In simple language, infrastructure refers to the basic structures and systems which are used by an organization or society to conduct its day-to-day work, for example, buildings, roads, water supply pipes, and electricity lines. Larkin (2013) defined infrastructures as “built networks that facilitate the flow of goods, people, ideas and allow for their exchange over space.” Resilience of a city, region, or country against climate change depends on the ability of infrastructures to withstand and absorb the additional stresses and shocks due to changing climate. Infrastructure is likely to represent about 66% of total adaptation costs globally by mid-2050 if the governments act to ensure that the essential services are provided to the citizens uninterrupted and work to protect them from the adverse impacts of climate change (Thacker et al. 2021).

Water Infrastructure encompasses any facility, equipment or structure related to production, conservation or storage, and delivery of water. It includes dams, canals, pipelines, desalination plants, pumping stations, storage projects including groundwater recharge and development, delivery and retention projects, wastewater treatment plants, and other equipment and facilities created for water conservation, together with any land, buildings and related equipment. Water infrastructures are needed because natural water availability seldom matches demands in terms of time, quantity, and quality. Water infrastructures help provide water of desired quality, in desired quantity, and at the place where it is needed. Water infrastructures have been around for thousands of years and yet the technological solutions employed for harvesting, storage and supply of water have changed little over time (Wells et al. 2021). But water infrastructure is highly vulnerable to impacts of climate change associated with hydrological alterations both on supply and demand side and would need appropriate adaptation measures. Damages to water infrastructures will disrupt quantity and quality of water supply to the intended users, leading to cascading impacts on health, sanitation, energy and industrial production, and environment. Damaged water infrastructure may not be able to control the threats due to floods and droughts.

Climate-resilient water infrastructure consists of systems and practices that are designed to withstand and adapt to climate change impacts like floods, droughts, and storms. Climate-resilient water infrastructures are designed, operated, and managed to absorb, recover, and adapt to the impacts of climate change, such as droughts, floods, water stress, rising sea levels, etc. Adaptive operation of water infrastructures, continuous monitoring and water management are important for resilient water management systems.

1.2 What is Resilience?

Impacts of climate change are felt primarily through the changes in the components of water cycle and changes in the properties of extreme events. Changes in the properties of floods, droughts, snow and glaciers, and rain may cause human and animal casualties, infrastructure damage, impact storage, disruptions and other harmful consequences. Climate change adaptation is necessary to reduce these adversities by increasing climate resilience.

Box 1 contains definition of some commonly used relevant terms. In broad terms, resilience denotes a system's ability to withstand, absorb, and adapt to shocks and transform into a better system (Lim et al. 2023). In the 4th Assessment Report, Intergovernmental Panel on Climate Change (IPCC 2007) defined resilience as “the ability of a social or ecological system to absorb disturbances while retaining the same basic structure, ways of functioning, capacity for self-organization, and capacity to adapt to stress and change”. In case of hydro-projects, resilience is the ability of infrastructure, policies, plans, and investments to cope with climate-related and other impacts. Fisher (2015) noted that there are more than 70 definitions of resilience in scientific literature and achieving resilience depends on what we mean by it. Broadly, as per the above IPCC definition, resilience is the ability of a system to bounce back after stress. It can also be seen as “the capacity of social–ecological systems to adapt or transform in response to unfamiliar, unexpected and extreme shocks”.

Box 1. Definition of some commonly used terms relevant to resilience (*Source*: IPCC 2021).

Exposure: The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

Hazard: The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

Resilience: The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/ or transformation.

Risk: The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Bahadur et al. (2010) have identified the following characteristics of a resilient system:

a) resilient systems have a high degree of diversity. For example, a water supply system may be drawing raw water from multiple sources.
b) have a high level of connectivity with stakeholders and institutions and high information sharing. For instance, an irrigation water supply project that organizes frequent interactions with farmers is likely to manage water deficits much better than a system where decisions are taken in isolation.
c) extent to which different forms of knowledge are blended to predict and manage the processes of change; more is the blending, better is the outcome.

d) have high level of redundancy. Hence, some parts of the system can fail without causing failure of the whole system. For example, if the spillway of a dam has some spare gates that can be used in an emergency, the chances of dam overflow may be nearly eliminated.
e) how fairly and equitably the stakeholders are represented, treated, and given access to resources, opportunities, and benefits. Risks should not be distributed in a disbalanced manner. If the spillway of a dam is properly designed and constructed but the dam body is weak, the dam may fail in an extreme event and in that case, extra strength of the spillway is of no use.
f) the degree of social cohesion and capital, allowing different individuals to be supported by social structures, embedded within. A society where people are aware of their duties as well as responsibilities and have mutual respect is likely to negotiate extreme events with ease.

Any system that effectively manages risks is considered to be more resilient. Note that both resilience and sustainability aim to create durable systems, but the two concepts are bit different. Resilience is concerned with the ability of the systems to bounce back after failure and adapt to change. Sustainability, on the other hand, focuses on maintaining the system in a stable state by minimizing adverse impacts. Basically, resilience is coping against shocks while sustainability is preventing them from happening.

Resilience is concerned with adaptability and recovery after a disaster (natural or human induced). A focus of resilience may be to prepare for likely disruptions, for example, by constructing infrastructure that can withstand shocks. Sustainability aims to keep a balance between needs – natural resources, environmental, and socio-economic - of current and future generations. To give examples, flood resilience can be increased by constructing embankments to protect an area from increasing riverine floods.

1.3 Measuring Resilience

Measurement of resilience is highly context dependent. It critically depends on the understanding and weight given to concepts such as coping, capacity, vulnerability and adaptive capacity. Several disciplines use the concept of resilience. Therefore, the approaches, tools and methods used to measure resilience reflect the diversity and features of the sectors where this concept is used. Ways to measure resilience assess elements such as technological capacity, political structures and decision-making processes, infrastructure, policies and institutions, economic status and growth prospects, skills and education levels of people, health of environment and natural resources, diversity of livelihood options, flows of knowledge and information and the speed and breadth of innovation.

The specific combination of measures chosen are typically based on available data rather than a normative approach. It is, therefore, the decisions on what aspects of a system to draw a boundary around, and indeed how a system itself is conceptualized, that continue to shape our knowledge of the interaction of processes that determine resilience in different contexts (Carpenter et al. 2010). Resilience indices have been developed and are being used in many sectors, including water to determine the resilience of a project under the current or projected scenarios or efficacy of an adaptation/mitigation measure.

One example is the Coalition for Disaster Resilient Infrastructure (CDRI), which is developing the Global Infrastructure Resilience Index (GIRI) (https://www.cdri.world) to aid planning, decision-making, and investment in disaster- and climate-resilient infrastructure. GIRI provides credible, fully comparable probabilistic risk metrics for every country across major infrastructure sectors, assessing risks from cyclones, floods, droughts, and multiple climate-change scenarios, while accounting for national capacities to manage and reduce these risks. Complementing such global initiatives, the International Water Management Institute (IWMI) has developed the Climate Smart Governance (CSG) Dashboard (Amarnath et al. 2023), an operational decision-support platform that integrates real-time early warning data, climate risk analytics, AI-enabled advisories, and institutional readiness indicators to support national and sub-national planning. Together, tools such as GIRI and IWMI's CSG Dashboard enable governments and development partners to freely and interactively access risk metrics and governance insights, strengthening evidence-based infrastructure resilience and investment prioritization.

1.4 Climate-Induced Threats and Future Risks to Water Infrastructures

Infrastructures degrade over time due to environmental stresses and the finite lifespan of materials. Climate change accelerates this process, either gradually through slow shifts or suddenly during extreme events, which can render assets non-functional within minutes. As climate pressures intensify, infrastructure faces additional stresses, and because many systems are interdependent, the failure of one asset—such as a large dam—can trigger cascading impacts on bridges, roads, agriculture, housing, and livelihoods far downstream. Recovery from such failures may take years.

Water infrastructures are vulnerable in different ways. Heavy rainfall and floods can overwhelm dams and diversions with excess water, sediment, or boulders, trigger bank collapses, or clog outlets. Canals may suffer from erosion or landslides, and pipelines can fracture or leak. Floods also damage wider network- roads, bridges, and buildings—disrupting mobility, trade, and service delivery. Droughts, while less directly damaging to structures, undermine services, reducing food production, power generation, navigation, and water security, while leaving reservoirs and canals dry and barren.

Extreme weather events—storms, floods, heatwaves, hurricanes, wildfires, and glacial melt—pose elevated risks to existing and future infrastructures, potentially causing service disruptions, human and animal casualties, property damage, environmental degradation, and economic losses (Takin et al. 2023). Projections indicate that the magnitude, duration, and frequency of such events will increase, and compound extremes (e.g., simultaneous drought and heatwaves) may become more common (IPCC 2018). Moreover, water-triggered disasters are likely to occur in regions that are historically less affected or with low prior frequency.

To safeguard water security, it is critical that water managers contain risks to existing infrastructure and ensure that new infrastructure is designed and constructed to be resilient in the wake of climate change. Whereas, in old water systems/infrastructures, design cannot be changed, and it is only the operation, management and maintenance of the system with adaptive water management options that can be explored. Table 1 provides a brief overview of the possible harm if various types of water infrastructures are not sufficiently resilient.

Table 1. Climate vulnerabilities, challenges, resilience strategies, and real-world impacts on different types of water

Type of Water Infrastructure	Key Vulnerabilities / Harms if Not Resilient	Main Challenges	Strategies to Improve Resilience	Real-world Examples
Urban Water Infrastructure (UWI) (pumps, treatment plants, pipelines, sewers, storage tanks)	• Pipe cracks/leaks → water loss, pollution, health risks • Pump/treatment failures → unmet demand, poor-quality supply • Storage tanks vulnerable to cyclones (esp. coastal) • Sewer failures → wastewater mismanagement	• Climate change stresses (heat, intense rainfall, cyclones) • Aging infrastructure • Lack of investment & poor maintenance • Rapid urbanization & population growth • Gaps in resilience assessment in developing countries	• System upgrade, decentralization, digitalization • Nature-based solutions (green infrastructure) • Preventive tools: GIS, WNTR, resilience awareness, efficient filters • Corrective actions: increase storage, policy reforms, DRR education • Integrated solutions combining technical & holistic approaches	• Cyclone Fani (2019, Odisha, India) disrupted urban water supply systems for weeks • Hurricane Katrina (2005, USA) caused major sewage treatment plant failures
Irrigation Infrastructure (canals, pumps, drains, storages, field systems)	• Droughts/floods damage supply & distribution • Canal breaches from intense rainfall • Sedimentation reduces capacity • Heat stresses → cracks in canals • Storage reservoirs losing space faster due to siltation • Reduced water for crops → food insecurity & poverty	• Growing water demand with climate & population pressures • Variability in flows & rainfall • Poor O&M and drainage facilities • Lack of sediment management • Weak farmer–agency collaboration	• Enhance water-use efficiency in crop systems • Good hydraulic design & operation • Adequate drainage & scour control • Improve sediment management in reservoirs/canals • Build surplus storage facilities • Regular maintenance & stakeholder training • Improve access to weather/flow forecasts • Strengthen farmer collaboration & governance	• Sardar Sarovar Canal breaches (2019 and 2025, Gujarat, India) damaged fields and villages • Indus Basin irrigation system repeatedly faces sedimentation challenges, reducing efficiency
	Failure of piers of aqueducts due to high scour, particularly under high flood conditions.	Piers of some aqueducts and bridges are may be uprooted due to high scour.	Strict regulation and monitoring of sand extraction; review of design norms.	Orsang Aqueduct built over the Orsang River, Gujarat (Rath, A., Patel, H.M. (2025). Estimation of Bridge

		Uncontrolled sand mining is one of the factors.		Scour Using HEC-RAS—A Case Study of Orsang Aqueduct. In: Pandey, M., Umamahesh, N.V., Ahmad, Z., Oliveto, G. (eds) Hydraulics and Fluid Mechanics, Volume 1. HYDRO 2023. Lecture Notes in Civil Engineering, vol 547. Springer).
Energy Infrastructure (hydropower & thermal)	*Hydropower* • Run-of-river projects: low direct risks, but silt management critical • Storage projects: high risks from inflow variability, extreme floods, sedimentation, slope failures • Earth & rockfill dams less resilient to climate risks *Thermal/Nuclear* • High water demand for cooling (esp. open-loop systems) • Higher water temperatures → reduced cooling efficiency • Plants in water-stressed areas vulnerable to shutdowns	• Changing inflows from rainfall/glacier melt → mismatched supply-demand • Sedimentation reducing reservoir capacity • Higher O&M needs for dams/slopes • Thermal power water dependence: 39% of India's thermal capacity in high-stress areas • Past losses due to water shortages	*Hydropower* • Revise design floods, spillway/storage capacity • Improve sediment management & slope stabilization • Increase monitoring/maintenance of earth & rockfill dams *Thermal/Nuclear* • Deploy efficient (closed-loop) cooling technologies • Develop alternate water storage/supply arrangements • Ensure new projects undergo water availability feasibility checks	• October 2023: GLOF in Upper Teesta Valley destroyed Teesta III hydropower dam and damaged several others • 2012–2016: 14 largest Indian thermal companies lost ~$1.4 billion in revenue due to water shortages (Kholod et al. 2021)

Flood Control Infrastructure (embankments, levees, dams, reservoirs, drainage)	• More frequent & intense floods • Higher sediment & boulder inflows from erosion • Sediment deposition reduces reservoir/river channel capacity → higher inundation • Structural failures → catastrophic damages to communities, agriculture, transport	• Climate-driven increase in extreme floods • Sedimentation reducing capacity & effectiveness • Static, outdated flood designs underperform • Socio-economic dependence on engineering systems • Inadequate risk monitoring/assessment	• Regular hydrological assessments of failure risk • Adaptive flood protection (dynamic targets) • Upgrade/strengthen critical structures • Improve sediment removal & reservoir operation policies • Integrate community memory, risk perceptions & preparedness • Combine structural & non-structural measures for resilience	• October 2023: Teesta GLOF caused massive downstream flooding, loss of 31 bridges, 25,900 buildings, and 270 km² of farmland • 2018 Kerala floods (India) overwhelmed dam releases, causing widespread inundation

1.5 Why Water Infrastructures Should be Resilient

Water infrastructures are needed because natural water availability seldom matches with demands in terms of time, quantity, and quality. Water infrastructures help providing water of desired quality, in desired quantity, and at the place where it is needed. Water infrastructures should be resilient for many reasons. Damages to water infrastructures will disrupt quantity and quality of water supply to the intended users, leading to cascading impacts on health, sanitation, energy and industrial production, and environment. Damaged water infrastructure may not be able to control the threats due to floods and droughts.

Infrastructure to supply irrigation water faces stresses due to extreme weather - droughts, floods, climate change, etc. Resilience of infrastructure created to supply irrigation water is the ability of these systems to withstand, adapt, and recover from shocks and stresses.

A frequently asked question is: "Why irrigation is so important?" This question has been answered in many different ways. For example, Namara et al. (2023) listed three reasons showing the importance of irrigation:

a) **Irrigation can increase agricultural productivity and reduce poverty: since** irrigated agriculture is a powerful climate adaptation strategy.

b) **Modernizing irrigation systems can support food security:** Experts emphasize that the key to feed the projected population of 10 billion people by 2050 is modernizing irrigation systems.

c) **Irrigated agriculture can grow food efficiently:** food systems are extremely vulnerable to the stresses induced by climate and other changes. Water has a transformative role in changing in our food systems, and it has not yet assumed a central role in their design.

Haile et al. (2024) used Actual Irrigation Water Withdrawals (AIWW) datasets to estimate future AIWW by use of five CMIP6 climate models, two Shared Socioeconomic Scenarios (SSP370 and 585) and a global hydrological model (H08). For the historical period (1981–2014), average irrigation water withdrawal (AIWW) ranged from 101.8 to 136.2 mm yr^{-1}, with a mean value of 120.5 mm yr^{-1}. Under the SSP370 scenario, projected average AIWW increases to 142.5 mm yr^{-1} during 2041–2070 and further to 145.5 mm yr^{-1} in the late-century period (2071–2100). Similarly, under the SSP585 scenario, average AIWW is projected to rise to 144.9 mm yr^{-1} in 2041–2070 and to 149.7 mm yr^{-1} by 2071–2100, indicating consistently higher irrigation water demand under the high-emissions pathway. It was found that higher AIWW increases are mainly concentrated in India, South China, parts of the United States, parts of Europe, and parts of South African and Latin American countries.

Many studies have been conducted in different parts of the world to determine how irrigation water requirements will change with climate. Typically, projected and downscaled climate data along with a crop model is used to estimate water requirements in future. For example, Makar et al. (2022) applied this framework using the CROPWAT 8 model to evaluate irrigation needs in a region of Egypt under climate change. Their analysis showed that the area is likely to experience almost no rainfall and a slight decrease in average temperature in the future. As a result, irrigation water requirements are expected to increase by about 4% if current agricultural practices remain unchanged.

Resilience of irrigation systems can be improved by the following measures:

a) Enhancing overall efficiency of water use for crop production systems,
b) Good hydraulic design and careful operation of facilities,
c) Adequate drainages in the fields to drain out excess water and salts,
d) Adequate facilities to store water during periods of surplus,
e) Limiting losses from the channels and field for the sake of scour control,
f) Regular attention to maintaining infrastructure,
g) Regular training and/or knowledge updating of the stakeholders/ managers about management options, covering both cultivation and water management,
h) Good collaboration among stakeholders including the farmers,
i) Good access to weather and hydrologic forecasts for all stakeholders,
j) Balancing between water demand and raw water availability.

1.6 Water Infrastructures Recovery

Like any other infrastructure, water infrastructure may also suffer damage and in such eventuality, the time in which a system becomes fully functional is important. Different types of water infrastructures, such as flood management systems, irrigation water supply networks, urban water supply systems, have different recovery timeframes. Recovery time for infrastructure depends on many factors:

a) Type of infrastructure and its size determine recovery time. Damage to a big dam would be tedious to manage but a small canal can be repaired relatively easily.
b) Damage Extent: if the damage to infrastructure is local, say, a short length of a canal bank is damaged, recovery time will be small and vice versa. If several kms of canal bed and banks are damaged, recovery time will be longer.
c) Accessibility of the Damage Center: If the damage occurs at a place which is well-connected by road/rail- network, material, machines, and manpower can be mobilized quickly and recovery would be fast. Repairs and recovery in remote or poorly connected places are slow.
d) Access to Resources: if the recovery team has easy access to materials, personnel with requisite skills, right equipment, spares, finances, etc., recovery will be quicker. A good practice is to keep some finances, materials, spares, etc. in reserve for use in emergencies.
e) Severity of the Event: The greater the severity of the damage-causing event beyond the design specifications, the higher the potential for damage and the more challenging the recovery process is likely to be.
f) Overall bureaucratic system: if the bureaucratic system is efficient, infrastructure recovery will be quicker.

1.7 Current and Likely Future Risks to Existing Infrastructure

Climate change is impacting water infrastructures through elevated risks of extreme weather events, such as storms, floods, and heatwaves. These events can (partly or significantly) damage and disrupt infrastructures, including those used for water supply for drinking and irrigation, transportation, energy generation, flood protection, and so on. Such damages lead to service disruptions, human and animal causalities, and economic losses.

In the future, the infrastructure would be subjected to all the risks that the current infrastructure is facing but there would be certain changes. Keeping in view the global warming trends and projections by IPCC (IPCC 2018), and other entities, the magnitude, duration and frequency of extreme events are likely to increase significantly. In addition, water triggered disasters – floods and droughts – are likely to occur more frequently in areas where these disasters were not occurring in the past or their frequency and intensities were low. Besides, in future compound extreme events (e.g., droughts and heat wave) might become more common. Takin et al. (2023) categorized climate change induced disasters in six categories: floods, heatwaves, drought, hurricanes, wildfires, and loss of glacial ice. In addition to damage to infrastructures, the impacts often cause loss of life, property damage, environmental degradation including loss of species and habitats, decreased productivity, financial losses, and falling quality of life. An important task for the water managers is to contain the risks to the existing infrastructure well within the limits and design and construct new infrastructures such that it is resilient in the wake of climate change.

Due to climate change, infrastructure to supply water for drinking and irrigation may have to face additional stresses as the pipes, canals, storage tanks will be exposed to more heat stresses, more intense rainfalls, and higher water demands. If the pipes develop crack and leak, this will result in wastage of water (leading to revenue loss) and people may receive polluted water in their taps, leading to health problems. Overhead storage tanks particularly in coastal areas are likely to face higher wind load due to more and intense cyclones.

Canals would be subjected to more intense rainfalls that may cause breach of banks particularly in filled-in reaches. If the parent river is carrying higher sediment load and it enters in the canal, it may be subjected to siltation, reducing the carrying capacity and rendering in operative. Canals will also be facing more heat stresses, leading to cracks.

As climate change is likely to increase variabilities in rainfalls and river flows, storage requirements to manage additional variations in rainfall and river flows will increase. At the same time, existing storage space is likely to deplete at higher rates due to increased sedimentation. In future, sediment management in reservoirs, canals, and pipes would require more attention.

1.8 Resilience Indices

Resilience indices have been developed and are being used in many sectors, including water to determine the resilience of a project under the current or projected scenarios or efficacy of an adaptation/mitigation measure.

The Coalition for Disaster Resilient Infrastructure (CDRI) is developing an index called the Global Infrastructure Resilience Index (GIRI) (https://www.cdri.world) to aid in planning, decision making and investment in disaster and climate resilient infrastructure. GIRI will provide credible and fully comparable probabilistic risk metrics for every country. It is a probabilistic risk assessment that covers global infrastructure sectors.

GIRI will measure resilience in water and other major infrastructure sectors and will estimate risk to major hazards, including cyclones, floods, and droughts, and will consider a range of climate change scenarios. Provisions will be made to consider the capacities of different countries to manage and reduce the risks. The users will be able to freely and interactively access and use the risk metrics produced through a platform.

2. Climate Resilient Infrastructure and its Key Features

Climate resilient infrastructure (CRI) is planned, designed, built, operated, and managed based on projections of changing climate conditions and adaptations (OECD 2020). CRI can withstand, respond to, and recover rapidly from disruptions caused by adverse climatic conditions. The process to ensure climate resilience continues throughout the life of the infrastructure. By doing this, the risk of climate-related disruptions may be reduced but it may not be fully eliminated.

Climate resilience of water infrastructures/systems is critically dependent upon their robustness since it is posing additional risks to water assets and the services they provide. Disruptions in services at a place usually lead to impacts within the catchment and beyond. Further, weak infrastructure can multiply climate-related risks. For example, intense rainstorms can trigger failures of a dam with catastrophic consequences downstream. Alternatively, extremely low and deficit rainfall may adversely affect the intended services to users/uses being provided by the given water infrastructure. Climate change is also likely to raise new demands or increase the magnitude of existing demands/stresses due to increased temperature and evaporative demands. Ageing water infrastructures may even be more prone to climate change impacts.

All these concerns suggest that the infrastructure should be climate resilient and rather than increasing vulnerability, resilience should be an integral concept of water infrastructures/systems. In practice, this means that water infrastructure/system should be planned, constructed and operated by anticipating, preparing, and adapting to the changing climate. Climate resilience should be ensured for all new infrastructures. Ageing infrastructure should be rehabilitated and operated to meet the likely climatic stresses. There are strong reasons to construct climate-resilient infrastructures because such assets will help in saving lives, provide reliable services, reduce maintenance expenditure, extend asset's useful life and generate many co-benefits. Every rupee invested in climate-resilient infrastructure yields about four rupees of benefits (Executive Summary, OECD 2024). Development of climate-resilient water infrastructure/system follows pathways that involve a continuing process of managing changes in accordance with evolving climate and other related driving forces.

2.1 Making Climate Resilient Water Infrastructures: Approaches and Pathways

The existing and future water infrastructures can be made more resilient if they adapt to the changing circumstances at the right time. Since the future is uncertain, the adaptation programs need to be flexible – they should be able to adapt as the drivers of climate change evolve. The programs should cover a wide range of anticipated climate impacts. Moreover, the adaptation programs should themselves be robust, covering a wide range of anticipated climate impacts. To promote climate resilient infrastructure (CRI) in India, actions are needed on several interlinked fronts.

Figure 1 highlights the multidimensional actions required to build climate-resilient water infrastructure/system in India and elsewhere. It underscores six interlinked areas: strengthening laws, policies, and plans; promoting good water governance across scales; adopting integrated water resources management (IWRM) with stakeholder participation; enhancing institutional capacity and skills; upgrading both existing and new infrastructures; and fostering environmental rejuvenation. Together, these elements provide a comprehensive framework that integrates governance, technical measures, institutional support, and ecological restoration to ensure sustainable and climate-resilient development pathways for the country (Jain et al. 2025).

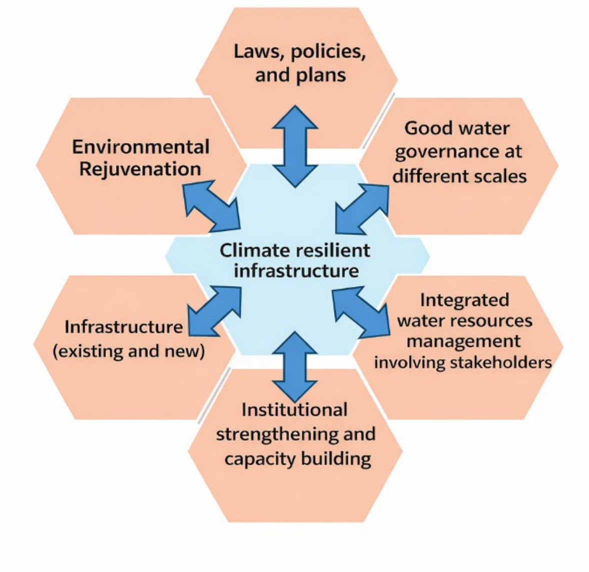

Figure 1. Actions needed to develop climate resilient infrastructures in India and its interlinkages (*Source:* Jain et al. 2025).

2.2 Infrastructure for Irrigation: Existing and New

Irrigation is central to agricultural productivity in India, where nearly half of the cultivated land remains rainfed and hence highly vulnerable to climate variability. Building climate-resilient irrigation (CRI) systems require strengthening both existing infrastructures and new investments, while managing demand and supply more efficiently and ensuring long-term sustainability.

Strengthening and modernizing existing infrastructure

Much of India's irrigation infrastructures/systems—large dams, canals, and hydro-projects built between the 1950s and 2000—face the challenges of aging, climate stress, and inadequate maintenance. Rehabilitation and upgrading are essential to safeguard water storage and delivery systems from floods, droughts, soil erosion, and other climate risks. The Dam Rehabilitation and Improvement Project (DRIP) is a key initiative in this regard, aiming to improve safety, operational efficiency, and institutional capacity.

Another critical challenge is the low per capita water storage capacity (200 m³), which is far below that of countries like the USA (6,000 m³) and China (2,200 m³). Enhancing India's storage infrastructure through both traditional and modern approaches will improve resilience against variability in rainfall and river flows. Historic systems such as the Ahar-Pyne in Bihar (box below) illustrate how community-led, nature-based designs can simultaneously harvest rainwater, mitigate floods, and ensure water availability under variable conditions.

Ahar-Pyne system of the Mauryan Empire

The Ahar-Pyne system of the Mauryan Empire, an excellent example of hydraulic structure for rainwater harvesting and participatory irrigation management. It is still in use in South Bihar and Chhota Nagpur. Pynes are channels carrying water from rivers; these were constructed from the rivers itself or from the Ahars. Ahars are low-lying fields with embankments that act as water reservoirs. This combined irrigation and water conservation system dates back to the Mauryan era that flourished in Magadh 2,000 years ago. The Ahar-Pyne system was also used for flood mitigation at that time. This scheme is very much suitable to the regions having scanty rainfall, hilly terrain with steep slopes, and soil with heavy clay causing excessive runoff.

The Ahar-Pyne system is an excellent example of CRI. (*photo:* X/Ministry of Jal Shakti)

Managing water demand in agriculture

As agriculture consumes nearly 80–85% of India's water, demand-side measures are crucial for building climate resilience and adaptation. Potential strategies may include:

- **Crop diversification and rationalized cropping patterns**: Reducing water-intensive rice, wheat, and sugarcane in favor of nutri-cereals, pulses, and oilseeds that require less water, offer better nutrition, and enhance resilience, especially in water stressed areas.
- **Climate-resilient crop varieties**: Promoting stress-tolerant cultivars with climate-smart agriculture practices to cope with droughts, floods, or pests.
- **On-farm efficiency measures**: Adoption of micro-irrigation (drip and sprinkler), laser land leveling, conservation agriculture, direct seeded rice, alternate wetting and drying (AWD) in rice, deficit irrigation, etc can reduce irrigation water use by 20–48%, energy use by up to 17%, and fertilizer use by nearly 20%. This helps enhance the resilience of the water systems.
- **Behavioral and policy nudges**: Campaigns such as Sahi Fasal encourage farmers to grow crops suited to their agro-climatic zones, while incentives for alternate DSR, crop diversification, micro irrigation, wetting and drying (AWD) in rice can lower both water use and greenhouse gas emissions.

Enhancing water supply and availability

Given projected increases in demand, irrigation infrastructure must adapt to changing water availability under climate and land-use shifts. Approaches include:

- **Improved storage and basin-scale planning**: Modeling studies, such as in the Narmada basin, highlight the need to account for climate-driven variability in river flows alongside growing irrigation demand.
- **Wastewater recycling and reuse**: With only 28% of India's 72 billion liters of daily sewage treated, there is significant scope for reuse of wastewater in agriculture, industry, landscaping, and recharging with safeguards. Recycling increases usable supply and reduces ecological degradation.
- **Renewable-powered irrigation**: Solar irrigation pumps under schemes like PM-KUSUM provide farmers with reliable, low-cost energy in areas with poor grid access, while reducing dependence on diesel. If coupled with groundwater governance measures, solar irrigation can enhance both water and energy resilience.

Real-time and adaptive management of water infrastructures

Generally, the water infrastructure is operated by considering the demands of the past and using data from historical or synthetic time series of hydrological variables. But the probability that an actual event will occur in the same way as prior events of the same type is small, particularly with changing climate scenario. In future, as the precipitation becomes more uncertain, demands for water for various uses such as irrigation, domestic, energy generation, will fluctuate more widely. Likewise, the river flows and inflows to the projects might change in more unpredictable manner because of alterations in water cycle due to climate change.

Infrastructure can be efficiently operated if the time interval between the occurrence of an event and the execution of the control adapted for that event is short. In real-time management, the operational decisions are based on short-term information. The definition of short-term varies in accordance with the purpose.

The term *real-time management* denotes the execution of a decision process concurrently with a physical system such that the results of the analysis based on on-line data are available in time to usefully control the physical system. Here on-line implies that the data about the system is received without any delay as the events take place and are immediately used. In real-time management, the release decisions for a finite future time horizon are taken, based on the condition of the infrastructure at that instant when these decisions are to be taken and the forecast about the likely inflows/demands over this time horizon, if available. After a certain time interval, new information about the reservoir state becomes available, the forecasts are updated, and the decisions are modified in light of these.

Benefits from real-time management are much higher when forecasts of inputs into the infrastructure and demands are available when the operating decisions are being taken. A forecasting algorithm is used to provide input forecasts for a finite number of future time periods based on the present state of the system as well as its past behavior. A mathematical model uses forecasts to determine the best decisions based on inputs, current state of the system and its demands (based on say growth stage of the crop, soil moisture, etc.) and determines how much water is to be released /diverted to meet the demands. Although the optimum releases are determined for a finite number of future time periods, they are implemented only for the immediate next time period. After this period, the next set of observations becomes available, and the entire process is repeated. This process of control of a system is known as **adaptive control –** the decision is adapted based on the feedback received from the system (Figure 2).

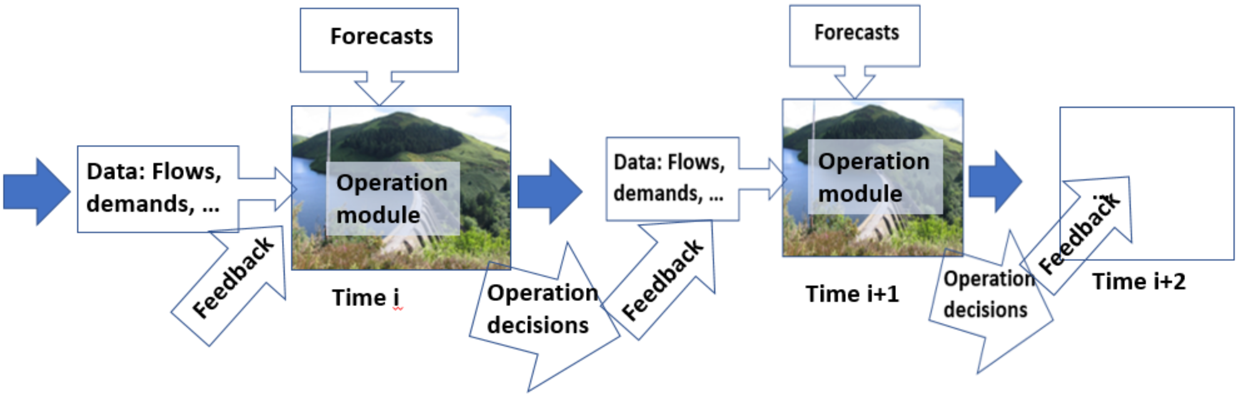

Figure 2. Adaptive feedback control of hydro-infrastructure using inflow forecasts.
(*Source*: author's analysis)

It is felt that real-time management of water infrastructure facilities will substantially add to climate-resilience.

3. Laws, policies, and plans (Regulations)

Mainstreaming climate resilience in water infrastructure requires enabling laws, policies, and institutional mechanisms. The National Water Policy (2012) provides the current framework but given the changing hydrological realities and emerging climate risks, an updated policy is essential. A revised policy should explicitly guide climate-resilient water infrastructure development by promoting water use efficiency across sectors, reducing demand, and protecting raw water sources.

Long-term planning is a prerequisite for building resilience. National-level initiatives such as the National Perspective Plan (NPP) for interlinking rivers, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) with its components "Har Khet Ko Pani" and "Per Drop More Crop," and the Atal Bhujal Yojana (ABY) for community-based groundwater management play critical roles in addressing spatial and temporal mismatches in water availability. These programs focus on irrigation expansion, water-use efficiency, and sustainable groundwater management, thereby contributing to CRI. Complementary regional and local plans further strengthen resilience by addressing site-specific challenges.

Legal frameworks also provide safeguards for water infrastructures. For instance, the Dam Safety Act (2021) mandates perpetual surveillance, inspection, and monitoring of dams, supported by the National Dam Safety Authority and State Dam Safety Organizations. These provisions aim to prevent dam-related disasters and ensure robust infrastructure performance under changing climate conditions. Extending similar mechanisms to other hydraulic structures, such as barrages and canals, would strengthen systemic resilience.

Several schemes and programs further embed resilience in practice. Atal Bhujal Yojana, for example, promotes participatory groundwater management, while the Watershed Development Component of PMKSY and the Catch the Rain campaign emphasize rainwater harvesting and water conservation for supply augmentation to build resilience. The Surface Minor Irrigation (SMI) and Repair, Renovation & Restoration (RRR) schemes restore water bodies, enhance recharge, and revive irrigation potential. The Central Ground Water Board's Master Plan for Artificial Recharge (2020) provides macro-level designs tailored to different terrains, while the Central Ground Water Authority (CGWA) mandates rainwater harvesting and recharge as prerequisites for groundwater abstraction.

Urban resilience is advanced through initiatives like the Atal Mission for Rejuvenation and Urban Transformation (AMRUT and AMRUT 2.0), which focus on water supply and recharge infrastructure in statutory towns. Rural resilience is supported by the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), which incorporates water conservation and water harvesting structures as part of natural resource management. Complementary efforts include Model Building Bye Laws (2016) that mandate rainwater harvesting provisions, the Jal Shakti Abhiyan (2019) in water-stressed districts, and the Mission Amrit Sarovar, which seeks to rejuvenate 75 water bodies in each district.

Despite these efforts, gaps remain in integration. Multiple programs in water, food, energy, and environment sectors often function in silos, with limited coordination (Jain et al. 2023). A Nexus approach—ensuring policy coherence, reducing duplication, and enhancing synergies across sectors—can significantly improve outcomes for climate-resilient water infrastructures/systems. It is important to strengthen institutional frameworks by ensuring that water management policies incorporate climate resilience principles by revising existing policies, enhancing coordination between different governmental agencies, and involving local communities in decision-making processes. In sum, India has established a robust legal and programmatic foundation for CRI, but strengthening interlinkages, updating the National Water Policy, and ensuring coherent implementation across scales are necessary steps to enhance resilience in the face of accelerating climate risks.

3.1 Integrated Water Resources Management (IWRM)

Integrated planning, management and operation of water infrastructures/systems, wastewater management, recycling and reuse of treated wastewater, with focus on key stakeholders' involvement is ideal for managing water and keeping ecosystems healthy. Target 6.5 under SDG 6 is concerned with Integrated Water Resources Management (IWRM). It aims to implement IWRM at all levels, including transboundary cooperation as appropriate by 2030. Noting the popularity of IWRM, Biswas (2008) pointed out that its impact on water management has been marginal. However, scientific literature contains many success stories including Australia's Murray-Darling Basin which is cited as an innovative application of IWRM principles (see, for example, Marshall et al. 2013). Castelletti et al. (2023) support use of adaptive water resources management or Model Predictive Control (MPC) for resilient development since it can help with increasing hydro-climatic variability and socio-economic transformations. UNEP-DHI Centre on Water and Environment have created an IWRM Data Portal (DHI 2024) to provide global data about implementation of IWRM for various countries.

In current times, IWRM should also consider climate resilient design of water and wastewater management infrastructure. Wastewater treatment plants should not be allowed to drown during floods. If a solid or liquid or waste management facility, is flooded, it may spread "toxic flood" over flooded areas and will lead to outbreak of diseases. Principles of IWRM across different spatial levels from basin to local scales are important in the context of building resilient water systems.

3.2 Institutional Strengthening and Capacity Building

To effectively and efficiently implement CRI, the tasks- institutional strengthening, including human capital, financial resources, and equipment require attention in India. In view of emerging challenges, government departments need to be re-orientated towards environmentally sound water management. More funds need to be allocated for research and development (R&D) in the water sector in India and more funding opportunities be created. A higher allocation for R&D in India will help in building greater resilience at all levels. Partnership with likeminded institutions including government, academia, research, NGOs, CSOs, and the

Private Sector is equally vital in building capacities across range of actors and institutions for driving home the understanding and need for implementing climate-resilient infrastructure .

3.3 Good Water Governance

Governance plays a central role in ensuring the effectiveness and sustainability of climate-resilient infrastructure (CRI). Good governance is characterized by forward-looking and proactive decision-making, efficient coordination across institutions, timely dispute resolution, and minimal overlap in jurisdictions. Although some degree of duplication is inevitable, effective communication and systematic knowledge-sharing across agencies enhance the overall resilience of infrastructure systems.

The National Water Policy (2012) underscores the need for integrated and basin-scale approaches, recommending the establishment of river basin boards to strengthen integrated water resources management (IWRM). Such institutional arrangements are critical to address fragmented responsibilities and ensure coordinated action across sectors and administrative boundaries. Financing is another crucial aspect of governance. Currently, most CRI investments are publicly funded, with public utilities, private actors, and international organizations increasingly contributing to infrastructure development and management. Broader stakeholder involvement brings diverse perspectives and technical expertise, resulting in more informed and inclusive decisions. However, sustainable financing requires reforms in pricing and resource allocation. Free or underpriced water services often lead to overuse and inefficiency. Equitable pricing mechanisms, as recommended in the National Water Policy, can promote conservation, ensure affordability for vulnerable groups, and generate resources for infrastructure maintenance and expansion. Regulatory support and political will are essential for implementing such reforms.

Governance framework also emphasizes inclusivity and participation. By engaging multiple stakeholders—government bodies, private sector, civil society, and communities—governance processes ensure that infrastructure planning and management reflect diverse needs and priorities. According to the World Bank (2010), governance is fundamentally about how power is exercised to manage a country’s resources for development. In the context of CRI, this means aligning institutions, policies, and practices to manage water and other natural resources efficiently, particularly during extreme climate events. As Tortajada (2016) highlights, good governance strengthens the resilience of both ecosystems and infrastructure by fostering accountability, transparency, and adaptive capacity.

3.4 Managed Retreat to Increase Resilience

An interesting measure to increase infrastructure resilience is by getting out of the way of threats. This approach is useful when the threat is unmanageable. This migration approach is termed as managed retreat (MR). Since ancient times, people have migrated to safe places to escape water and climate related long-term disasters. Migration is practiced in current times as well. Temporary relocation is a common strategy to minimize damage during cyclones or similar events.

Responding to natural disasters, people adopt different measures. Managed retreat (MR) is "*the purposeful, coordinated movement of people and assets out of the harm's way*". Here, the word "retreat" should not be viewed in a negative sense; it means "strategic relocation" and migration is often seen as a measure of last resort (Jain and Karmakar, 2022). Well thought-out plans are necessary to ensure that infrastructure is not relocated from one hazard prone area to another.

Although MR is an old concept, it is gaining prominence now because some emerging threats due to climate risks can't be managed by conventional measures alone. Flood plain zoning, which is commonly used to avoid flood damages is a form of MR. The Netherlands has successfully implemented a project known as "*Room for the river*" wherein people living in areas adjacent to rivers which are likely to be inundated by floods, were relocated to safer places. In Japan, new towns have been built to relocate people hit by tsunami generated by a massive earthquake of 2011. In India, people are temporarily relocated to shelters in case of severe cyclones and floods and this has significantly reduced deaths/miseries due to calamities. Managed retreat is considered as a mitigation option as it "*avoids the unmanageable (mitigation)*" instead of "*managing the unavoidable (adaptation)*."

India's coastline is about 7,500 kilometers long. By the year 2100, 36 million people are likely to be living in areas prone to coastal flooding. Some critical infrastructure in Indian coastal cities (Mumbai, Chennai, Kochi, Vishakhapatnam, Thiruvananthapuram, Mangalore, etc.) may be submerged due to sea water level rise by 2050. Maps of urban sprawl of coastal cities such as Chennai and Mumbai show that the number of people living near the coasts is increasing. In addition, large (and increasing) population is living dangerously close to rivers and other disaster-prone areas.

In many documented cases (Kendrapada district, Odisha; Sundarbans in Ganga-Brahmaputra delta; and Majuli island, Brahmaputra valley, Assam) relocation was found to be an adaptation option less preferred due to high economic and socio-cultural cost. However, it is emphasized that in many situations, relocation turns out to be the only viable option. In India and other developing countries, many people live in disaster-prone areas. In future, people living on lands likely to be affected by water would have to be relocated inland, preferably in the same State. New developments in disaster-prone/vulnerable areas should be carried out after thorough risk assessments.

3.5 Nature-based Solutions for Climate-Resilient Infrastructure

Nature-based Solutions (NbS) are strategies inspired by, supported by, or modelled on natural processes to address societal, environmental, and economic challenges in sustainable ways. The International Union for Conservation of Nature (IUCN) defines NbS as actions to "protect, sustainably manage, and restore natural and modified ecosystems, benefiting people and nature at the same time," while the European Commission emphasizes solutions that leverage nature to tackle diverse challenges. OECD (2020) further consolidates these definitions, highlighting NbS as measures that maintain or enhance ecosystem services while addressing social, environmental, and economic risks. When NbS are used to adapt to climate change specifically, they are often referred to as ecosystem-based adaptation (EbA).

NbS have emerged as a cost-effective, flexible approach to enhancing climate resilience of infrastructure while delivering social and environmental co-benefits. Unlike conventional grey infrastructure, which is static and can fail under extreme events, NbS are dynamic, adaptive, and regenerative, providing robust protection against climate hazards while supporting biodiversity, groundwater recharge, and carbon sequestration.

3.5.1 Key Features and Benefits of NbS

- **Climate Resilience and Risk Reduction**: NbS leverage natural ecosystems to reduce exposure to floods, storm surges, heatwaves, and erosion. Coastal wetlands, mangroves, coral reefs, and oyster reefs act as natural barriers, mitigating coastal flooding and erosion, while riparian vegetation and wetlands buffer riverine flood risk. For example, during Cyclone Dana (Oct. 2024) in Odisha, India, the Bhitarkanika mangrove forest significantly reduced damage to adjacent coastal areas. Urban NbS—including bioswales, bioretention ponds, permeable pavements, green roofs, street trees, and green façades—alleviate urban heat, reduce strain on wastewater systems, and manage flash floods. Even small-scale interventions, such as grassed tramway verges in Norway, can improve infiltration, reduce flooding, and recharge groundwater.

- **Complementarity with Grey Infrastructure**: NbS are not a substitute for engineered infrastructure but complement it, creating hybrid systems that are more resilient and cost-effective. For instance, dams provide flood storage but may fail during extreme events, as demonstrated by the 2023 Glacier Lake Outburst Flood (GLOF) in Upper Teesta. Combining dams with NbS—such as wetlands and riparian buffers—enhances flood management, reduces sedimentation, and prolongs the operational lifespan of built infrastructure. Globally, green roofs and urban wetlands have been adopted to protect stormwater systems from heavy precipitation events and urban flooding.

- **Flexibility and Adaptation**: Natural systems are inherently adaptive. Mangroves can regenerate after storm damage, wetlands migrate with changing hydrology, and floodplains temporarily store excess water during peak flows. Unlike static grey infrastructure, NbS adjust to shifting climatic conditions, maintaining performance under variable flows, sea-level rise, or heat events. For example, the Itaipu hydropower project in Latin America planted over 44 million trees in conservation areas, reducing sedimentation, stabilizing river flows, and improving dam operations. These conservation areas are now recognized as a UNESCO Biosphere Reserve.

- **Ecosystem Services and Socio-Economic Benefits**: NbS generate multiple co-benefits beyond hazard mitigation. They enhance biodiversity, sequester carbon, improve water quality, and contribute to food and water security. Mangroves globally store an estimated 4.19×10^9 tons of carbon, while wetlands can reduce nitrate concentrations in water by over 80%, often outperforming conventional treatment systems. NbS also enhance livelihoods and tourism potential; for example, India's MISHTI program (2023–2028) aims to restore ~540 km² of mangroves, creating carbon sinks of 4.5 million tons and supporting sustainable income for coastal communities. Economic analyses suggest NbS often cost less than grey infrastructure while providing additional benefits. Coastal NbS have been estimated to save billions in avoided damages By acting as protective coastal barriers to cities, they save an estimated USD 65 billion a year in storm and flood damages (Earth Security 2020).

3.5.2 Applications of NbS in Resilient Water Infrastructure

- **Flood Management and Water Storage**
    - Floodplains: Naturally occurring river floodplains, such as those along the Ganga, can temporarily store floodwaters, allowing infiltration and aquifer recharge. Even modest interventions across multiple floodplains can conserve significant volumes of water and mitigate downstream flooding.
    - Subsurface storage: Depleted aquifers can be used to store excess floodwater, as demonstrated by IWMI's Underground Transfer of Floods for Irrigation (UTFI) program. Integrating aquifer recharge with reservoirs and inter-basin transfers enhances water availability, moderates floods, and improves sustainable water management.
    - Urban wetlands and ponds: Reduce peak runoff, improve water quality, and provide supplementary water storage for municipal and agricultural use.

- **Coastal Protection**: Mangroves, coastal wetlands, and coral reefs act as first-line defences against cyclonic surges, storm waves, and erosion. Their restoration, protection, and sustainable management stabilize shorelines while providing fisheries, carbon storage, and recreation benefits. MISHTI program exemplifies large-scale mangrove restoration aimed at both resilience and livelihood generation.

- **Urban Water and Heat Management**: Bioswales, permeable pavements, and green roofs reduce urban flooding, recharge groundwater, and provide cooling through evapotranspiration. Trees and green façades mitigate heat islands, improve air quality, and enhance urban liveability. These solutions are especially valuable in dense urban environments with limited grey infrastructure capacity.

Figure 4. (left) Where feasible, the spaces around tramways have been unpaved and grass covers have been provided rainfall can infiltrate in the ground. This NbS contributes to addressing flooding as well as ground water recharge. Picture from Norway, taken by the author (Aug. 2024). (right) Flood plains of Ganga River at Balawali, near Laksar, Dist. Haridwar. (*photo*: Sharad Jain).

3.5.3 Challenges and Barriers to Adoption of NbS

Despite their multiple benefits, the adoption of NbS remains limited due to several barriers. Policy and regulatory frameworks still tend to favour conventional grey infrastructure, which is perceived as simpler and lower risk. NbS also face spatial and temporal constraints, as they require adequate land and often take longer to generate measurable outcomes. Technical and capacity gaps further hinder implementation, since ecosystem-based design, monitoring, and maintenance skills are often lacking within public and private agencies. Governance challenges add complexity, as NbS initiatives span multiple sectors—such as water, environment, urban development, and disaster management—demanding strong cross-agency coordination. Financial constraints also persist, with global spending on NbS standing at only USD 154 million annually, far below what is needed for climate adaptation and biodiversity restoration.

Overcoming these challenges requires integrated planning, capacity building, monitoring, stakeholder engagement, and innovative financing mechanisms, including subsidies, green bonds, and partnerships with NGOs. Effective NbS implementation also depends on strengthening design and maintenance skills through training for engineers, planners, and communities; establishing monitoring and feedback systems to track ecosystem performance; ensuring community participation to foster ownership and prevent encroachment; and promoting knowledge sharing through databases of best practices and inter-agency collaboration to scale successful models.

3.6 Resilience Science Must-Knows

Ahead of the recently concluded COP30, a new report, titled “Resilience Science Must-Knows”, was developed by Future Earth, the Global Resilience Partnership, Stockholm Resilience Centre, and partners worldwide (Norström et al. 2025). The central message of this report is: resilience must be central to how we make decisions about our shared future. It encourages readers to evolve — to adapt, learn, and find new ways to thrive in a rapidly changing world. Further, resilience is about learning from crises, keeping options open, and enabling societies to transform toward fairer, more sustainable futures. Resilience is also about how everything connects. Climate, biodiversity, and development are deeply linked.

The *Nine Must-Knows* are:

1) Resilience is critical for navigating accelerating risk.
2) Resilience requires balancing the capacities to cope, adapt, and transform.
3) Investing in resilience today reduces costs tomorrow.
4) Resilience is a cycle of learning and innovation.
5) Diversity is essential for resilience to thrive.
6) Relationships among people and with nature build resilience.
7) Governing and negotiating trade-offs is key to resilience.
8) Empowering agency unlocks resilience.
9) Address power imbalances to foster equitable resilience.

4. Conclusion

Resilience is viewed as a continuous process consisting of learning, adapting, and strengthening basic structures, actors and functions. Since the exposure, nature and magnitude of stress on water infrastructures will keep on changing (and possibly increasing) in future due to climate risks, management of resilience must follow a set of dynamic activities. Resilience is a comprehensive concept that enables the consideration of multiple risks, shocks, and stresses, along with their impacts on infrastructure and ecosystems and vulnerable populations. To increase resilience, capacity of individuals, communities, and institutions needs to be improved, in terms of abilities to learn, innovate, and adapt. For building effective climate resilient water infrastructures, the principles of adaptability, diversified water resources, robustness, integration of NbS. with grey infrastructure, data-driven planning and decisions, and community and stakeholder engagement is vital. A range of data from diverse sectors is required to optimally implement CRI. Robust systems for the continuous monitoring of water resources and climate data by upgrading meteorological and hydrological stations and utilizing advanced technologies such as remote sensing and GIS for better data accuracy is critical for resilient water infrastructure. A higher allocation for R&D will help in finding better solutions to enhance resilience of water systems. By embracing innovative solutions to accommodate future climate risks, diversified water supply and use system with integrated nature-based solutions, fostering partnerships, revisiting water policies to internalize climate resilience into water management and encouraging community participation, a climate-resilient water infrastructure/system can be achieved.

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