CDRI
Coalition for Disaster Resilient Infrastructure

Global Infrastructure
Resilience Working Paper

Irrigation Infrastructure Risk and Food Security

GIR IRRIGATION
2025 WORKING PAPER

This work is a product of the Coalition for Disaster Resilient Infrastructure (CDRI), as part of a working paper series under the ambit of the second Global Infrastructure Resilience Report (GIR 2025). This Working Paper on *'Irrigation Infrastructure Risk and Food Security'* presents recent findings on the patterns and scale of disaster risk to irrigation infrastructure, examines its links with local and global food security, and identifies opportunities for enhancing infrastructure and food systems resilience. It may be accessed at https://cdri.world/resilience-dividend/global-infrastructure-resilience-report-second-edition/.

This document is a launch edition and may undergo minor changes subject to updates in the analysis.

All papers under the GIR 2025 Working Paper Series are available on the official website of CDRI, accessible on the web link mentioned above. They provide detailed background material, methodologies, analyses, and case studies for each chapter of the report. The papers will be released sequentially starting November 2025 through 2026.

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Acronyms

ADPC	Asian Disaster Preparedness Center
AAL	Average annual loss
CABI	Centre for Agriculture and Biosciences International
CDRI	Coalition for Disaster Resilient Infrastructure
DRI	Disaster resilient infrastructure
FAO	Food and Agriculture Organization of the United Nations
FEWsheds	Planning for Food, Energy and Water sheds
FMIS	Farmer-managed irrigation systems
FSIN	Food Security Information Network
GDP	Gross domestic product
GIR	Global Infrastructure Resilience
GIRI	Global Infrastructure Risk Model and Resilience Index
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
Lao PDR	Lao People's Democratic Republic
OECD	Organisation for Economic Co-operation and Development
PGA	Peak ground acceleration
PGD	Peak ground displacement
PGV	Peak ground velocity
PML	Probable maximum loss
SOLAW	The State of the World's Land and Water Resources for Food and Agriculture
SSP	Shared Socioeconomic Pathway
USDA	United States Department of Agriculture
UNESCO	United Nations Educational, Scientific and Cultural Organization
WFP	World Food Programme
WRI	World Resources Institute
ZORA	Zürich Open Repository and Archive

Glossary

Average Annual Loss (AAL)
A measure of annualized future losses over the long term, derived from probabilistic risk models (UNISDR, 2013).

Climate adaptation
Adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects. It refers to changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change (UNFCCC, n.d. a)

Climate change
A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (UNFCCC, 1992).

Climate finance
Local, national or transnational financing, drawn from public, private and alternative sources of financing, that seeks to support mitigation and adaptation actions that will address climate change (UNFCCC, n.d. b).

Disaster risk management
The application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses. Disaster risk management actions can be distinguished between prospective disaster risk management, corrective disaster risk management and compensatory disaster risk management, also called residual risk management.

- Prospective disaster risk management activities address and seek to avoid the development of new or increased disaster risks. They focus on addressing disaster risks that may develop in future if disaster risk reduction policies are not put in place. Examples are better land use planning or disaster-resistant water supply systems.
- Corrective disaster risk management activities address and seek to remove or reduce disaster risks which are already present, and which need to be managed and reduced now. Examples are the retrofitting of critical infrastructure or the relocation of exposed populations or assets.
- Compensatory disaster risk management activities strengthen the social and economic resilience of individuals and societies in the face of residual risk that cannot be effectively reduced. They include preparedness, response, and recovery activities, but also a mix of different financing instruments, such as national contingency funds, contingent credit, insurance and reinsurance and social safety nets.

Disaster risk
The potential loss of life, injury, and/or destroyed and damaged assets, which could occur in a system, society, or community in a specific period, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.

- Extensive risk, the risk of low-severity, high-frequency hazardous events and disasters, mainly but not exclusively associated with highly localized hazards.
- Intensive risk, the risk of high-severity, mid- to low-frequency disasters, mainly associated with major hazards.

Essential services
The services provided by infrastructure, such as water and wastewater, power and energy, transport, telecommunications, health, and education that are essential for social and economic development. (Definition adopted in this Report)

Infrastructure
Individual assets, networks and systems that provide specific services to support the functioning of a community or society

Infrastructure lifecycle
The series of stages during the lifetime of an infrastructure asset, starting from planning, prioritization and funding to the design, procurement, construction, operation, maintenance, and decommissioning.

Infrastructure governance
The capacity to plan, finance, design, implement, manage, operate, and maintain infrastructure systems (Hertie School of Governance, 2016).

Infrastructure systems
Arrangements of infrastructure components and linkages that provide a service or services.

Reliability
Ability of an infrastructure asset or system to perform the desired function based on specified requirements over time without interruption or degradation.

Resilience
The ability of individuals, households, communities, cities, institutions, systems, and society to prevent, resist, absorb, adapt, respond, and recover positively, efficiently and effectively when faced with a wide range of risks, while maintaining an acceptable level of functioning and without compromising long term prospects for sustainable development, peace and security, human rights and well-being for all. (UN, 2020).

Resilience dividend
The value of reduced future asset loss and damage avoided service disruption, wider social, economic, and environmental co-benefits, and reduced systemic risk, that accrue over the lifecycle of an infrastructure system. (Definition adopted in this Report)

Resilient infrastructure
Infrastructure systems and networks, the components, and assets thereof, and the services they provide, that can resist and absorb disaster impacts, maintain adequate levels of service continuity during crises, and swiftly recover in such a manner that future risks are reduced or prevented.

Systemic resilience
The resilience of social, economic, territorial, and environmental systems at all scales, that conditions the ability of infrastructure assets and the services they provide to resist and absorb disaster impacts. (Definition adopted in this Report)

Systemic risk
In the context of infrastructure, systemic risk is a cumulative risk to a system as an outcome of physical, biological, social, environmental, or technological shocks and stresses. These may be internal or external to the system. Impact on individual components of the system (assets, networks, and subsystems) becomes systemic due to interdependence and interactions between them.

Key Messages

Disasters are a driver of food insecurity

Disasters are a major and growing driver of food insecurity, disrupting food availability, access, and stability. Climate change is increasing the frequency and intensity of hazards, amplifying both local agricultural losses and global food system shocks, particularly for vulnerable populations.

Irrigation infrastructure is a critical food security lever

Irrigation infrastructure underpins a disproportionate share of global food production. Although irrigated land represents a minority of cultivated area, even modest damage to irrigation infrastructure can trigger large yield losses, income shocks, and food price volatility that far exceed repair costs. Thus, food security is closely linked to the resilience of infrastructure, including irrigation, farm-to-market transportation, energy for processing, and communication.

Systemic importance outweighs asset value

Economic losses to irrigation infrastructure often appear small compared with other sectors, yet their systemic importance is far greater. Disruptions to water delivery cascade across farming systems, labour markets, and supply chains, magnifying impacts on national and regional food security.

Different irrigation systems face distinct risks

Surface, sprinkler, drip, and subsurface irrigation systems are exposed to hazards in different ways and face varying types and levels of vulnerability. Their design, water source, and maintenance requirements shape vulnerability to floods, droughts, storms, earthquakes, and slow-onset processes such as sedimentation and salinization.

Underinvestment and ageing assets increase fragility

Long-term declines in public investment and maintenance have left many irrigation systems ageing and fragile. Outdated designs and deteriorating components mean that even moderate hazards can cause significant failures, prolong disruptions, and increase food security risks.

Governance and institutions strongly influence outcomes

Weak governance, unclear maintenance responsibilities, and poor cost recovery amplify the impacts of disasters. In such contexts, institutional failures can turn hazards into systemic crises, delaying repairs and prolonging agricultural losses well beyond the disaster event itself.

Global risk is uneven, but widespread

Global irrigation infrastructure faces nearly $2 billion in average annual disaster losses, concentrated in tropical and subtropical regions. South and Southeast Asia, parts of Africa, and small island states face particularly high relative risks due to hazard exposure and dependence on irrigation. The Global Infrastructure Risk Model & Resilience Index (GIRI) suggests that countries such as Vietnam, Bangladesh, India, and Thailand can expect annual damages.

Floods and climate-driven extremes dominate risk

Floods account for the largest share of global irrigation risk, followed by cyclones, droughts, and heat stress. Under future climate scenarios, expected losses increase sharply, especially in regions already exposed to hydrological extremes and water scarcity.

Climate change creates a compounding risk dynamic

Climate change accelerates damage to irrigation assets, increases reliance on irrigation for adaptation, and expands exposed infrastructure. This triple-risk dynamic raises long-term losses unless resilience investments keep pace with growing demand and climatic uncertainty.

Irrigation failures have global market impacts

Damage to irrigation systems in major producing regions can reduce exports, trigger price spikes, and transmit food insecurity across borders. Irrigated agriculture supplies key staples and high-value crops; as a result, local infrastructure failures can have global consequences.

Investing in resilience delivers high returns

Strengthening irrigation resilience through better design standards, maintenance, governance, and financing reduces losses and shortens recovery times. Since irrigation underpins food systems, resilience investments generate a substantial resilience dividend for food security and livelihoods.

1 Introduction: Disaster Risk, Irrigation Infrastructure, and Food Security

Disasters are a primary driver of local and regional food insecurity, affecting availability, access, and stability within food systems and placing vulnerable populations at risk (FSIN, 2025; de Haen & Hemrich, 2007; Habiba et al., 2016; Bené, 2020). The increasing frequency and intensity of extreme weather-related disasters, including floods, storms, droughts, and wildfires, as well as recurring geophysical events such as major landslides and earthquakes, devastate food production and local food systems, increasing the risk of the impacts becoming global (Galanakis et al., 2025; Ogwu et al., 2024; Elnashar & Elyamany, 2023).

Direct impacts on food security include harvest losses and reduced crop yields, which reduce local food availability and, depending on scale, affect national and regional food security (Klomp & Hoogezand, 2018). At the global level, rising temperatures and droughts remain the primary drivers of agricultural production losses, followed by floods, storms, and pest outbreaks, with developing nations and smallholder farmers disproportionately affected (Hamed et al., 2025; FAO, 2025; Li & Gorelick, 2025).

Disasters can also have long-term effects on food systems. Recurring disasters degrade soil quality, slow down recovery, and destabilize entire food systems, making it harder to maintain steady supplies and risking prolonged food shortages (Khatri et al., 2024; Gomiero, 2016). Beyond affecting land and production, major disasters affect food security by damaging transport infrastructure, limiting labour demand or supply, often resulting in rising food prices and supply chain disruptions across the globe, thereby compounding the effects of hunger (Puma et al., 2015). Even in the context of small-scale disasters, immediate and long-term impacts can be significant, particularly when they recur or are seasonal. Households that depend on agriculture, livestock, or fisheries are most at risk, as they lose both food and livelihoods when disasters strike. Poor communities in urban centres can be equally affected by downstream impacts, which manifest as price hikes and food scarcity in local markets.

Disasters can negatively impact all infrastructure assets, affecting food security. Damaged ports and airports mean agricultural outputs intended for trade and export cannot reach their destinations, potentially affecting food availability there and incomes in areas of origin. Destroyed power stations and electricity grids, as well as oil and gas infrastructure, directly affect farmers' ability to irrigate and maintain their lands, as well as to harvest and process crops. Disruptions to telecommunications can trigger food price spikes and broader market volatility, particularly in increasingly connected regional and international markets.

The impacts of disasters on irrigation infrastructure are even more direct. Irrigation infrastructure is both a cornerstone of global food security and a point of vulnerability. Disasters—whether floods, storms, droughts, or geophysical events—threaten to undermine irrigation systems' capacities to promote agricultural production in many regions, with direct consequences for the availability and affordability of food worldwide. Although the economic risk to irrigation infrastructure from disasters may seem minor compared to that to transport, energy, or housing assets, it has disproportionate effects on food security. This is because irrigation functions as a critical 'lever' for agricultural productivity and stability. Even relatively modest damage and direct losses disrupt crop water supply over large areas, amplifying impacts on yields, rural incomes, and food availability far beyond the replacement cost of the damaged assets (FAO, 2021). Therefore, irrigation infrastructure plays a crucial role in strengthening the resilience of agricultural systems, as long as it is managed as a cohesive system capable of withstanding and recovering from disasters. Failure to do so can make irrigation infrastructure systems part of the problem rather than part of the solution.

With steadily increasing global food demand, areas under irrigation will continue to grow and are estimated to reach up to 800 million ha by 2050 (Puy et al., 2020). At the same time, climate change already intensifies hydrological extremes and is predicted to accelerate the risk of infrastructure damage (IPCC, 2022). In addition, existing irrigation assets, including water storage infrastructure, are ageing. Without adequate maintenance and investment in rehabilitation, they are at risk of failure during disaster events (Scanlon et al., 2022; Perera et al., 2021). Therefore, risks to food security will continue to grow unless adequate investments are made in irrigation infrastructure.

Despite a growing recognition of the risks, a significant research gap remains in understanding disaster risk specific to irrigation infrastructure. The Global Infrastructure Risk Model and Resilience Index (GIRI) was developed in 2023 and includes several infrastructure sectors and hazards, providing a first global overview of disaster risk to infrastructure (see Chapter 2 for more information on probabilistic risk modelling and GIRI). In 2025, the model was expanded to address the knowledge gap in irrigation infrastructure risk. This paper presents an overview of the most significant findings and discusses their implications for food security.

1.1 How to Understand Disaster Risk and Resilience

Disaster risk is defined as the likelihood that disasters of a given intensity and impact will occur within a specific time period. Risk is the outcome of interactions between three components: hazard, exposure, and vulnerability (see Figure 1.1). Hazard describes the probability and magnitude of a potentially damaging event—such as an earthquake, tsunami, flood, or tropical cyclone—and is typically characterized by its frequency and severity. It can be amplified by climate change in the case of weather-related disasters. Exposure refers to the quantity, type, and economic value of assets located in hazard-prone areas. Vulnerability reflects the degree to which those assets are prone to damage or loss.

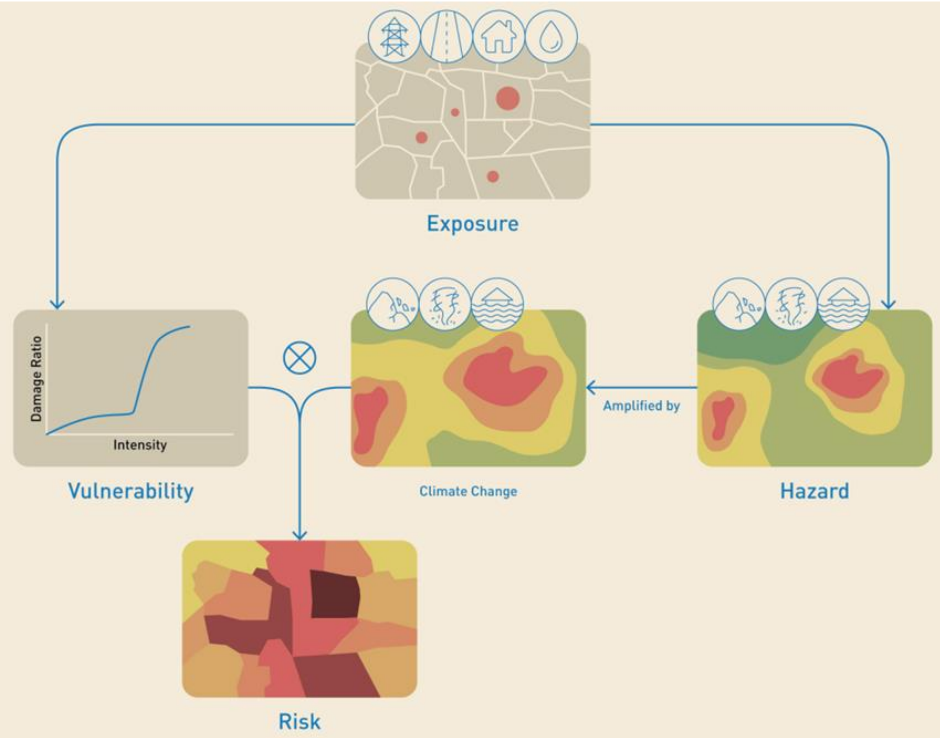

Figure 1.1 The risk equation

Source: CDRI (2023a)

To estimate infrastructure asset risk, modellers must first identify and map the main hazards in the regions where assets are located. Hazards are shaped by features such as tectonic faults, cyclone paths, and floodplains. Climate change, environmental degradation, and land use changes can alter hazards, including floods, landslides, strong winds, storm surges, and droughts. Climate change is expected to intensify hazards that threaten infrastructure assets and affect their ability to deliver the services for which they were designed. For instance, prolonged droughts can reduce the electricity-generating capacity of hydropower facilities. The second step involves determining the location of each infrastructure asset and estimating its economic value, which together define the asset's exposure.

Finally, vulnerability functions are applied to different infrastructure types and hazard intensities to estimate the level of damage likely to occur. These functions are developed through statistical analysis of loss data across varying hazard severities, drawing on empirical and historical evidence, analytical modelling, and expert judgment. Vulnerability is largely influenced by construction quality and compliance with resilience standards. When standards are high and consistently enforced during construction and maintenance, infrastructure assets may face lower risk even in areas with significant hazard exposure.

The conventional approach to infrastructure resilience largely emphasizes engineering solutions to enable infrastructure assets to withstand and absorb the effects of geological and climate-related hazards. This perspective prioritizes stronger design codes, innovative materials, and advanced technologies. However, such an approach is limited in scope, as truly resilient infrastructure assets are those that are part of broader resilient systems, and which are thereby able not only to absorb hazard impacts but also to respond to and recover from disruptive events and shocks. CDRI, therefore, defines disaster-resilient infrastructure as "Infrastructure systems and networks, the components, and assets thereof, and the services they provide, that are able to resist and absorb disaster impacts, maintain adequate levels of service continuity during crises, and swiftly recover in such a manner that future risks are reduced or prevented." (CDRI, 2023b).

The Global Infrastructure Resilience (GIR) 2025 report presents a comprehensive framework for analysing infrastructure resilience that goes beyond viewing infrastructure as isolated physical assets (CDRI, 2025). Instead, it considers infrastructure as interconnected networks that deliver essential services to individuals, communities, businesses, and the wider economy. This systems-based perspective highlights that resilience depends not only on the robustness of individual assets but also on how networks function during disruptions and how users interact with and adapt to service failures.

Within this framework, infrastructure resilience is defined through three core capacities. First is the capacity to absorb shocks, which determines how well infrastructure can resist and withstand the impacts of disasters without significant loss of functionality. Second is the capacity to respond, referring to the ability to manage damage, maintain basic service continuity, and implement emergency actions during a crisis. Third is the capacity to recover, which involves restoring services as quickly as possible while incorporating lessons learned to reduce future losses and damages.

These capacities apply across three levels: infrastructure assets, the services they provide, and the users who depend on them. Resilience is therefore not a static attribute, but a dynamic cycle. When a disaster occurs, infrastructure performance typically drops from normal operating levels to a degraded state or even complete failure. The severity of this drop reflects the asset's ability to absorb shocks. During the degraded phase, emergency response and clean-up activities take place, followed by planning, design, and procurement for repairs and reconstruction. Recovery then restores performance, ideally to an improved level through 'building back better.' A critical element of this phase is learning from the disaster, including updating risk assessments with new hazard data and climate change projections, to ensure reconstruction enhances long-term resilience.

Many infrastructure agencies traditionally focus on strengthening the capacity to absorb shocks through improved standards, retrofitting programmes, better construction supervision, and enhanced maintenance. While these measures are important, the GIR 2025 report stresses that they are insufficient on their own. The economic and social impacts of disasters are closely linked to the duration of infrastructure service disruptions. Delays in response and recovery amplify losses for households, businesses, and communities.

The resilience cycle also applies at the network and service level. Here, recovery depends on factors such as , while effective 'building back better' requires analysing vulnerabilities across interconnected systems. For infrastructure users, resilience depends on preparedness, access to timely and reliable information, two-way communication with service providers, and the ability to find alternative solutions when services fail.

To strengthen resilience, infrastructure agencies and asset owners must invest in all three capacities. Absorptive capacity can be enhanced through proactive maintenance, retrofitting, and systems that convert early warnings into protective actions. Response capacity relies on preparedness, coordination with disaster management and emergency services, pre-arranged repair resources, and rapid damage assessment technologies such as drones. Recovery capacity is strengthened through post-disaster evaluations, adoption of innovative and nature-based solutions, and higher resilience standards in reconstruction.

Together, these efforts reduce damage, shorten response and recovery times, and minimize service disruptions in case of future disasters. The cumulative benefits of strengthening all three capacities are described as the 'resilience dividend,' encompassing reduced asset losses, avoided service interruptions, social and economic co-benefits, and lower systemic risk over the infrastructure lifecycle.

1.2 Disaster Risk to Irrigation Infrastructure System Types and Components

Agricultural irrigation systems need to be adapted to specific crops, landscapes, and hydro-meteorological conditions. They can be broadly classified into four main types, each differing in efficiency, application method, and suitability: surface, sprinkler, drip, and subsurface irrigation. The choice of system ultimately depends on factors such as water availability, soil characteristics, crop requirements, and economic feasibility. However, disaster risk should also be considered, as each of these irrigation systems is exposed and vulnerable to physical hazards in unique ways because of how they deliver water, due to their infrastructure requirements, and their dependence on environmental stability.

Surface Irrigation

It is one of the oldest and most common methods that relies on gravity to distribute water across fields through channels or furrows. Water flows over fields due to gravity and infiltrates into the soil; common sub-types include basin, border-strip, and furrow irrigation. Flood irrigation is widely used in rice paddies and level basins where water blankets the field. Furrow systems guide water through trenches between crop rows. While simple and low-tech, it often results in high water losses due to evaporation, uneven water distribution, and runoff (Bos et al., 2005). Poor maintenance can also lead to waterlogging due to sediment accumulation. Overall, surface systems are most affected by water scarcity or flooding. Surface irrigation is highly vulnerable to droughts because it requires large volumes of water to flow over fields. Floods or heavy rains can also damage channels and furrows, reducing system efficiency and increasing soil erosion.

In July 2007, heavy rain over three days caused severe flooding and waterlogging in the Liuying irrigation district in Juye County, Shandong Province, China (ADPC, 2008). The district relies on a surface-irrigation canal system that was already suffering from poor maintenance, sediment buildup, and leaking channels. As a result of the flood, several villages in the district were inundated for about a week, leading to the collapse of houses and a reduction in agricultural output. This disaster illustrates how a surface irrigation system—with its exposed trenches and channels—can be especially vulnerable to extreme rainfall: flooding damaged the infrastructure, and waterlogging crippled both homes and crop production.

Sprinkler Irrigation

In contrast, sprinkler irrigation supplies water under pressure through pipes and nozzles, mimicking rainfall, providing more uniform coverage and adaptability to varied terrain, though it remains vulnerable to wind drift and evaporative loss. In many countries, including the United States, Australia, China, and those in Europe, sprinkler systems have replaced traditional systems due to superior water efficiency, yield enhancements, and integration with precision technologies such as automatic timers and soil moisture sensors (Chauhdary et al., 2024). Sprinkler irrigation can be disrupted, however, by strong winds and storms, which scatter water unevenly and reduce effectiveness. Extreme temperatures pose a risk, as freezing can crack pipes and nozzles, while droughts or heatwaves increase evaporation losses, straining already limited water supplies.

Several examples from the United States, where sprinkler irrigation is widely employed, illustrate the risks. In 2024, Hurricane Helene caused major damage to farms in Georgia. Amid widespread destruction, a roughly 300-foot-long sprinkler irrigation system was overturned, with steel pipes bent and welded joints broken by storm winds (Bynum, 2024). The agricultural losses from Helene are estimated to be in the billions, particularly affecting cotton, pecan, and vegetable farms (Zimmerman, 2024). Also in Georgia, a severe storm with tornado activity in January 2017 caused significant damage to farms and irrigation infrastructure in the southern parts of the state. Large-scale sprinkler systems were affected, as several pivot towers were flipped over by high winds, making them inoperable (Thompson, 2017). Farmers reported that damaged pivots limited their ability to irrigate the next season, and many had to adjust which crops they grew because they no longer had full irrigation capacity.

Drip Irrigation

Also known as micro-irrigation, this method delivers water directly to the root zone through emitters and tubing, greatly enhancing water-use efficiency while reducing weed growth and soil erosion. Placing water drop by drop directly to plant roots drastically reduces evaporation and runoff losses, making this approach particularly well-suited to arid regions and high-value crops (Bhavsar et al., 2023). However, micro-irrigation systems are fragile in the face of contamination or physical damage, and they are sensitive to clogging from sediment or contamination after disasters such as floods or dust storms. They also rely on pumps, filters, and tubing, which can be damaged in disasters, making repairs costly.

In Kenya, a study found that many smallholder farmers discontinued using low-cost drip kits, largely because of unreliable water supply and maintenance problems, particularly during droughts (Kulecho & Weatherhead, 2005). In parts of the Sahel region, micro-irrigation systems suffered from clogging (due to fine particles, algae, and iron precipitation) in low-pressure drip networks. The required filtration and maintenance exceeded farmers' technical capacity, making the systems unsustainable and more vulnerable to disaster damage (Keita et al., 2022). In Zimbabwe, during the 2016–2017 rainy season, small farmers using drip systems had pipes that were washed away or developed leaks during floods, and clogged emitters reduced system efficiency (Chidavaenzi et al., 2021).

These documented cases of systemic failure and damage to drip irrigation systems, particularly in low-income contexts, show how environmental stresses and disasters can seriously disrupt them.

Subsurface Irrigation

Also referred to as seepage irrigation or wicking systems, subsurface irrigation uses buried drip lines or porous pipes. It reduces evaporation and improves root-zone uptake, but it demands a higher initial investment and careful maintenance (Goyal, 2021). This type of irrigation system is used primarily in regions where water is scarce, where high-value crops justify the higher installation costs, and where the required financial resources are available. These include some parts of the Middle East, India, the US, and Australia, where it may be adopted for high-value crops.

Subsurface systems can carry high risks if natural hazards disrupt underground infrastructure. Subsurface irrigation is less affected by evaporation or wind, but it is highly vulnerable to soil disturbances from earthquakes, floods, or landslides that can shift, or block buried lines. They are harder to inspect and maintain because large parts of the system are buried, making failures harder to detect. However, some types of agricultural irrigation, particularly surface systems, can increase landslide risk, providing an argument for greater investment in subsurface systems where feasible. Yet, because of its high installation and maintenance costs, damage from disasters can be economically devastating. As a result, adoption rates remain limited, and documented cases of the impacts of disasters on subsurface systems are likewise limited. Meanwhile, much of the academic and market literature on such systems focuses on water efficiency, design, and maintenance, rather than on disaster resilience or failure (More, n.d.).

1.3 Vulnerability and Infrastructure Risk at the Global Level

Several factors determine the susceptibility of infrastructure to disaster damage and can be found to varying degrees in different income regions and agricultural production systems across the globe. Ageing and poorly maintained assets increase the vulnerability of irrigation systems during stress. Without sufficient maintenance and investments in rehabilitation, concrete linings crack, gates corrode, and pumps wear out, making them highly vulnerable to damage even from small-scale disasters. While no global assessments of the current status and quality of irrigation infrastructure exist, several studies and recent examples confirm that ageing and poorly maintained irrigation systems are increasingly at risk.

Investment trends over time indicate that the irrigation sector may be severely underfinanced. For instance, World Bank lending for irrigation steadily increased for about 30 years starting in 1950, peaking around 1980 (see Figure 1.2). It experienced a sharp decline afterwards, similar to many other infrastructure sectors, and never recovered. While irrigation lending accounted for up to 10 percent of the World Bank's overall lending in the late 1970s, it now accounts for less than 1 percent (Plusquellec, 2024).

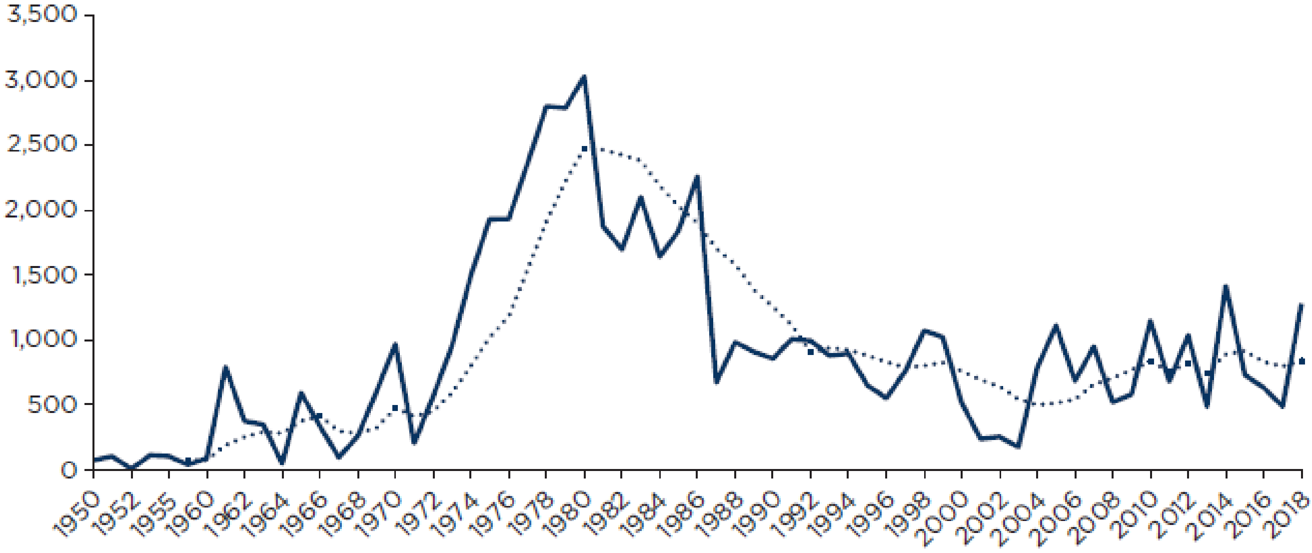

Figure 1.2. World Bank's annual commitments to irrigation projects, 1950–2018*

Source: Plusquellec (2024)
Note: *in constant 2010 US$ millions.

Similarly, in Organisation for Economic Co-operation and Development (OECD) countries, public support linked to agricultural water use, of which irrigation is a key component, has declined markedly over time. Total water-related agricultural support fell from $18.7 billion[1] in 1995 to $6.8 billion in 2019 (OECD, 2022). Within this overall reduction, funding specifically targeted at irrigation contracted even more sharply, with domestic producer support for irrigation dropping from $2.5 billion in 1989 to approximately $480 million by 2019. Over the same period, the proportion of support that directly incentivized irrigation use fell from 88 percent to 46 percent (OECD, 2022).

Public investment remains the main financing channel for irrigation infrastructure. Based on limited data from countries with national accounts on water infrastructure spending, global annual spending is estimated at $2.3 billion, or 0.05 percent of gross domestic product (GDP) in 2017 constant prices (Joseph et al., 2024). The same estimates suggest a spending gap of $3.5 billion per year, even in a low-cost scenario that subsidizes irrigation infrastructure alone and reduces agricultural demand.

As a result, many irrigation systems remain in poor condition because of insufficient investment and inadequate maintenance (United Nations, 2024). For instance, studies of Turkey's irrigation policies indicate that, despite ambitious targets to expand irrigated areas, the share of irrigation investments in public budgets has declined since the early 2000s. This decline has contributed to ageing infrastructure and unmet modernization needs (Abdullahi & Arisoy, 2022). Development practitioners similarly observe that coordination failures among farmers and agencies can hinder investment in shared systems, leading to deferred maintenance and incomplete rehabilitation (Asthana, 2022). In Central Asia, irrigation infrastructure is estimated to be approximately 50 years

[1] $ refers to US$.

old on average. Furthermore, 70–80 percent of fixed water-sector assets, including irrigation infrastructure, are thought to be suffering from poor maintenance and resulting damage. These translate into significant economic losses from infrastructure deterioration (Vinokurov et al., 2023). In many parts of Africa and Asia, large-scale irrigation infrastructure is considered outdated and in need of upgrading or replacement (IWMI, n.d.).

In 2024, a large group of multilateral development banks published a joint report on water security financing, setting a baseline for tracking investment in the sector, including in irrigation infrastructure, and calling for scaled-up support for climate-resilient irrigation systems (World Bank, 2024).

Inadequate design standards mean systems that were designed under past climate conditions may not withstand today's extremes (Nasser et al., 2025). Dams that were designed based on historical, 'stationary' climate regimes now face elevated risks due to more intense precipitation, altered hydrological patterns, and increased sediment loads. Flood protection embankments, too, may be overtopped by new rainfall intensities, while reservoirs may not handle increased sediment loads. This risk increases significantly under future climate scenarios, as various studies across contexts show (Ho et al., 2025; Wan Ariffin et al., 2025).

Design standards in many places have not been updated or stress-tested against future climate scenarios, leaving infrastructure potentially less resilient. Water scarcity can also lead to failures in irrigation infrastructure and assets. Research from Brazil underscores the risk of water stress caused by increasingly variable and extreme future hydrological conditions, leading to failures in current reservoir designs and directly affecting the efficiency of irrigation systems (Chaves et al., 2023).

Further, institutional factors can exacerbate existing risks and create new ones, with infrastructure regulation, financing, and management arrangements being particularly critical. Poor cost recovery, weak water user associations, disputes over water rights, or unclear maintenance responsibilities heighten vulnerability (Gany et al., 2019).

The 2010 Pakistan floods wreaked havoc on the country's agricultural production, with large-scale damage to irrigation infrastructure. Weak governance, including unclear roles and responsibilities for maintenance, and limited investment in the upkeep and regular monitoring of asset and system performance, led to major canal breaches in Sindh and Punjab (Khan et al., 2021). One of these, the Tori Bund breach, caused flooding across large areas of agricultural land and widespread crop failure. The disaster reports highlighted that funds allocated for embankment strengthening were either misused or postponed, while provincial irrigation departments and district administrations debated who was responsible for emergency bund repairs. Unauthorized settlements and agriculture occurred in canal right-of-way areas due to weak enforcement.

In Nepal, the 2015 Gorkha earthquake damaged hundreds of traditional hill irrigation systems—especially farmer-managed irrigation systems (FMIS)—affecting approximately 122,000 hectares of irrigated land (DiCarlo et al., 2018). While the earthquake's intensity was a major factor, the extent of damage was thought to be exacerbated by institutional and governance gaps (DiCarlo et al., 2018; Parajuli et al., 2024). While FMIS are traditionally managed directly by farmers, after the earthquake, the division of responsibilities between central government agencies, local governments, and water user groups was unclear. To worsen matters, there was weak institutional support before the disaster: limited government oversight, no updated FMIS inventory, and minimal funding for earthquake-resilient upgrades. Finally, slow post-disaster coordination led to overlapping mandates and responses by multiple agencies at the local and national levels, further delaying funding and reconstruction. As a result, irrigation in many areas was disrupted for an entire cropping season, reducing rice and vegetable production.

In Kenya, recurrent floods along the Tana River in 2006 and thereafter resulted in significant damage to irrigation infrastructure in the area. Flooding breached canals and washed out pump stations and river intakes, destroying infrastructure serving thousands of hectares. While the physical hazard was real, governance and institutional shortcomings increased the system's vulnerability (Oduori & Njeru, 2016; Daily Nation, 2020). The National Irrigation Board had already been facing long-standing issues of inadequate funding, poor record-keeping for maintenance, and slow response times. As in the other examples, unclear allocation of roles between local communities and government meant that community and farmers' associations assumed the government would maintain headworks, while the government assumed communities would handle routine canal upkeep. And limited enforcement of zoning regulations meant settlements close to embankments increased pressure on canals or diverted floodwaters into at-risk areas.

Socioeconomic pressures—such as rapid population growth or movement—and high dependency rates resulting from agricultural intensification and land-use change, increase demands on irrigation infrastructure, often stretching systems beyond design capacity. Where this occurs in hazard-prone regions such as South Asia, Sub-Saharan Africa, and the Middle East, these developments significantly amplify disaster risks. However, no region is unaffected by these combined pressures. Increasing irrigation demand, coupled with low precipitation and recurrent droughts, has led to a hydrological collapse in the Axarquía region of southern Spain (Junquera et al., 2024). Reservoir levels fell nearly to zero, and groundwater levels dropped too due to long-term over-demand, especially from fruit plantations growing mangoes and avocados. Limited regulation of water use and inadequate enforcement of water quotas further exacerbated the situation.

Population growth not only increases demand on irrigation infrastructure but also results in the encroachment of settlements on canal banks or in reservoir buffer zones, thereby increasing exposure. For example, regular flooding associated with water reservoir bank encroachment in India resulted in major flooding in 2021 (Deccan Chronicle, 2021). Many such examples exist that illustrate how socioeconomic pressures and governance failures combine with ageing infrastructure systems and weak designs to create the paradox of progress, in which irrigation infrastructure becomes a source of risk.

2 The Global Irrigation Infrastructure Risk-Scape: Hazard, Exposure, and Vulnerability

The Global Infrastructure Risk Model and Resilience Index (GIRI)'s inclusion of irrigation infrastructure significantly broadens and deepens our understanding of disaster risk to infrastructure worldwide. Irrigation networks—comprising canals, diversion structures, pumping stations, reservoirs, and drainage systems—represent one of the largest and most spatially distributed forms of infrastructure globally, especially in low- and middle-income countries. Their exclusion from previous risk assessments meant that a major category of assets, and the populations and economies they support, were only partially represented in global disaster risk metrics. Therefore, incorporating irrigation infrastructure creates a more inclusive, representative, and realistic global picture of risk. Importantly, this inclusion highlights the central role of water management in climate resilience and food security.

Irrigation systems are directly exposed to multiple climate-driven hazards, such as drought, floods, sedimentation, glacial lake outburst floods, and riverbank erosion. At the same time, they are a foundation for food production, rural livelihoods, and water security. By modelling irrigation assets alongside other infrastructure sectors, GIRI acknowledges that climate resilience is not only about protecting energy grids, transport networks, or buildings—it is also about safeguarding the water-control systems that sustain agriculture and regulate seasonal variability, and buffering communities against climate extremes.

BOX 1. Probabilistic Risk Modelling and GIRI

The insurance industry relies on probabilistic risk modelling to estimate the full range of losses that disasters might cause. These models generate financial indicators used to set insurance premiums for households and businesses and to design larger risk-financing tools, such as catastrophe bonds. They work by simulating many possible disaster scenarios based on a scientific understanding of how hazards behave, creating large numbers of synthetic events. This approach provides a much fuller picture of potential risk than historical data alone. However, most traditional catastrophe models are built for specific insurance markets or groups of assets, and they are often not available to governments, infrastructure planners, or even the people who buy insurance.

To address this gap, CDRI created GIRI in 2023, the first publicly available fully probabilistic model designed specifically to estimate the risks facing infrastructure assets from major geological and climate-related hazards. The GIRI model is designed to cover several hazards, including floods, landslides, tropical cyclones, droughts, earthquakes, and tsunamis. It assesses risk using a probabilistic approach across a broad range of infrastructure sectors: power stations and electricity grids; roads and railways; ports and airports; water and wastewater; irrigation; telecommunications; oil and gas; education; health; and buildings. GIRI's main inputs are hazard models with comprehensive sets of simulated events, climate change scenarios that reflect a lower and upper bound of global warming levels, a geo-localized exposure database of assets and networks in each infrastructure sector and assigned economic values for each, and newly developed vulnerability functions for over 50 infrastructure archetypes.[2]

The main risk metrics generated by GIRI are the average annual loss (AAL) and the probable maximum loss (PML) at specific return periods, as well as sectoral loss distributions at the country level (see Figure 2.1). The national AAL for irrigation infrastructure is calculated as the value relative to the total value of a country's irrigation infrastructure and is usually presented as per mille (‰).

[2] For more information on the GIRI model, associated metrics as well as its limitations, please see https://cdri.world/resilience-dividend/global-infrastructure-risk-model-resilience-index/, https://cdri.world/global-infrastructure-resilience-report-2025-capturing-the-resilience-dividend-2 and relevant technical working papers.

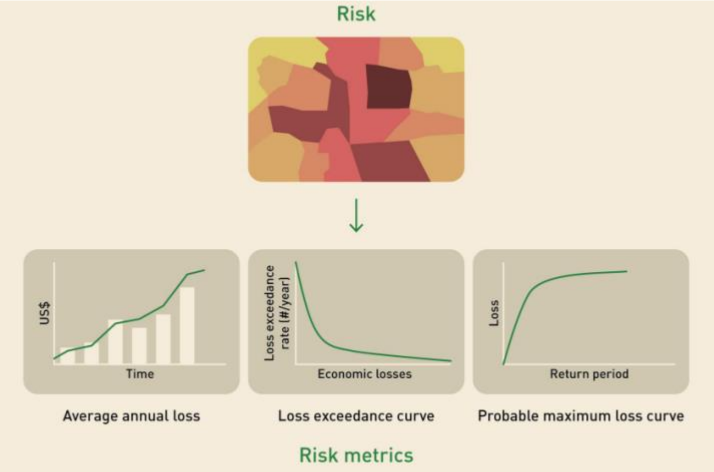

Figure 2.1. GIRI risk metrics

Source: CDRI (2025)

AAL is a particularly common measure in the insurance industry. It reflects the average annual amount which, when accumulated over time, would be equivalent to all future losses. Conceptually, the AAL corresponds to the fair pure premium required annually to cover all possible losses. This means that the AAL estimates the contingent liabilities for each infrastructure sector in each country or territory. It is a practical and compact metric that presents the expected or average loss that may be experienced in the long run. For any given infrastructure sector and country, it measures the resources that governments would need to set aside, on average, each year to cover future asset loss and damage.

AAL is a crucial risk indicator because it integrates the impact of hazardous events on vulnerable exposed elements into a single value. It is the most robust risk metric—not only because it summarizes the loss-occurrence process in a single number, but also because it is relatively insensitive to uncertainty, reflecting the mathematical expectation of annualized losses.

Yet, PML is often the preferred metric in planning processes because the concept of a return period is generally easier to interpret. The return period is the expected time between events with a given impact, i.e., events that exceed a given loss threshold. Mathematically, it is calculated as the inverse of the exceedance rate, and loss values can be selected for any particular return period. Choosing a return period depends on the risk aversion or appetite of the risk owner or insurer.

As such, the GIRI outputs directly support evidence-based decision-making in the context of climate adaptation, disaster risk reduction, and sustainable infrastructure development.

Source: CDRI (2023a)

By expanding the model to incorporate irrigation infrastructure, GIRI now offers a better, more inclusive understanding of disaster risk to infrastructure across the globe. This inclusion also acknowledges the critical role of water management in climate resilience. Finally, by extending multi-hazard risk evaluation to agricultural systems, the model enables a more integrated perspective on the interdependencies among infrastructure sectors, environmental systems, and climate dynamics.

2.1 Exposure of Agricultural Irrigation

The GIRI exposure model for irrigation infrastructure uses spatially detailed data on the number of irrigated hectares, combined with information on the type of irrigation water sources (surface water and groundwater). The latter is particularly important, as the water source determines the design of intake, conveyance, and distribution systems, and allows for assigning different vulnerability profiles to different systems (see Section 2.2). Further, categorizing the irrigated area by water source helps assign an economic value to the different exposed assets.

It is important to note that the economic value of irrigation systems is often significantly lower than that of assets in other infrastructure sectors. Irrigation infrastructure is often comprised of relatively simple technologies that do not require complex engineering, high-tech materials, or specialized manufacturing facilities. As such, they are less capital-intensive, reducing replacement cost. A significant proportion of irrigation infrastructure, particularly in low-income countries, uses locally sourced materials and involves embankment and canal construction that does not require high-skilled or specialized labour. Many components of an irrigation system are also designed with shorter life cycles in mind. As a result, frequent maintenance and periodic rehabilitation costs may be included in the total costs, at least in principle, thereby reducing initial and replacement costs.

From a disaster risk perspective, the combination of underinvestment and low-complexity technology means the baseline infrastructure stock is both low in value and highly vulnerable: embankments may be fragile, control structures outdated, and drainage systems insufficient, increasing the likelihood that moderate hazards will cause significant service disruptions. Yet when disasters strike, official damage assessments often focus on major urban and transport infrastructure, reinforcing a cycle where rural water systems receive limited attention and funding, even though their disruption has direct repercussions for national food security and rural welfare.

Finally, irrigation infrastructure has far lower regulatory requirements for safety and structural standards than, for example, energy or transport infrastructure, further reducing the replacement cost and per-unit value of a system's assets (Nikkels et al., 2019). As a result of these factors, the overall monetary losses associated with disaster risk are relatively low; however, the implications of large-scale damage to irrigation infrastructure for food security and market failure can still be catastrophic.

Globally, one must distinguish between areas equipped for irrigation and those actually irrigated by different systems (Meier et al., 2018; Nhamo et al., 2024). For GIRI, the starting point is global data on the number of hectares and the location of areas equipped for irrigation (see Figure 2.2).

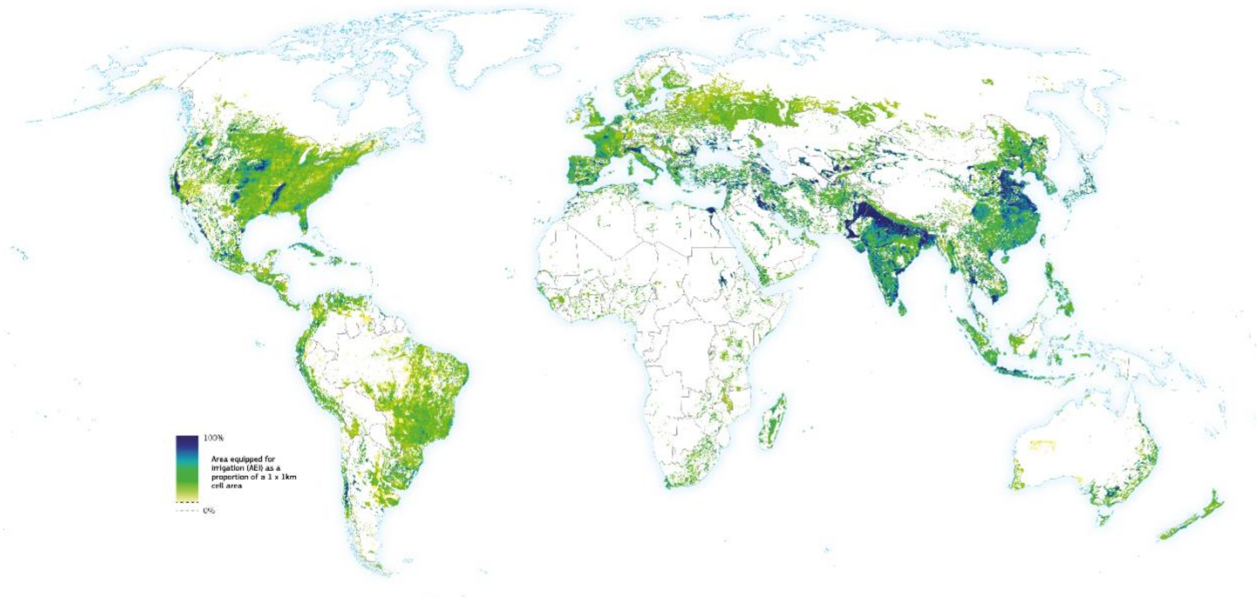

Figure 2.2. Areas equipped for irrigation worldwide

Source: Siebert et al. (2013).

The economic valuation in GIRI was done by estimating replacement costs for the different infrastructure technologies and levels of complexity. It was calculated using unit replacement cost (in $/ha), differentiated by water source and national income group, and presented as a gridded distribution: (INGENIAR Risk Intelligence, 2025).

The maps of exposed economic value reveal clear patterns linked to the type of water source. The groundwater-based irrigation map highlights high-value concentrations across South and East Asia—especially India, Pakistan, and northern China—where large, irrigated areas rely heavily on wells, pumps, and associated energy systems (see Figure 2.3). Additional clusters appear in the western United States, northern Africa, and the Middle East, where aquifer-fed irrigation is essential in dry climates.

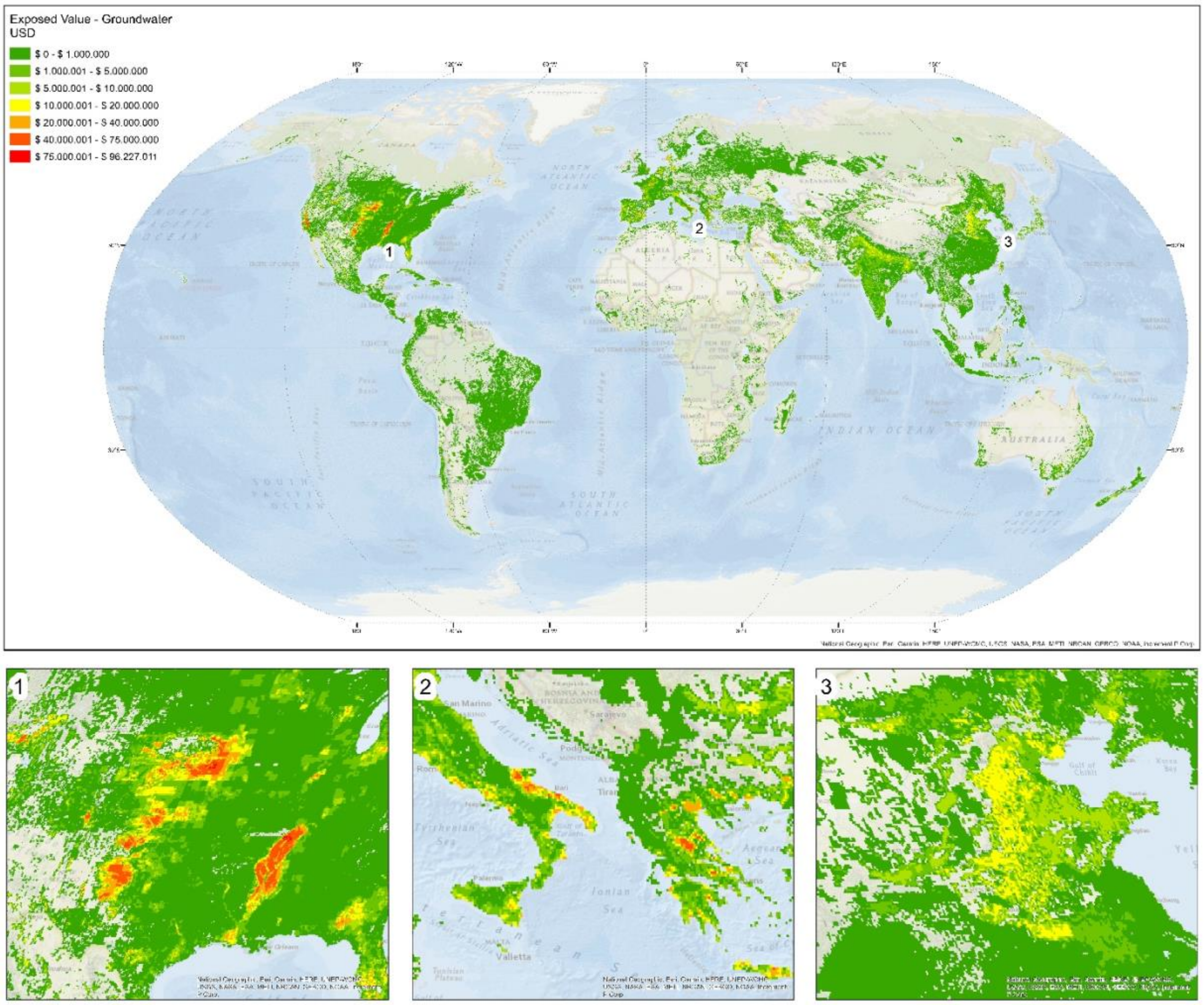

Figure 2.3. Exposed value of groundwater-based irrigation infrastructure

Source: INGENIAR Risk Intelligence (2025)

In comparison, the surface water–based irrigation map shows wider, more continuous coverage that aligns with major river basins and deltas, such as the Ganges–Brahmaputra, Nile, Mississippi, and Mekong (see Figure 2.4). These regions show high total values because of their extensive canal networks and distribution systems.

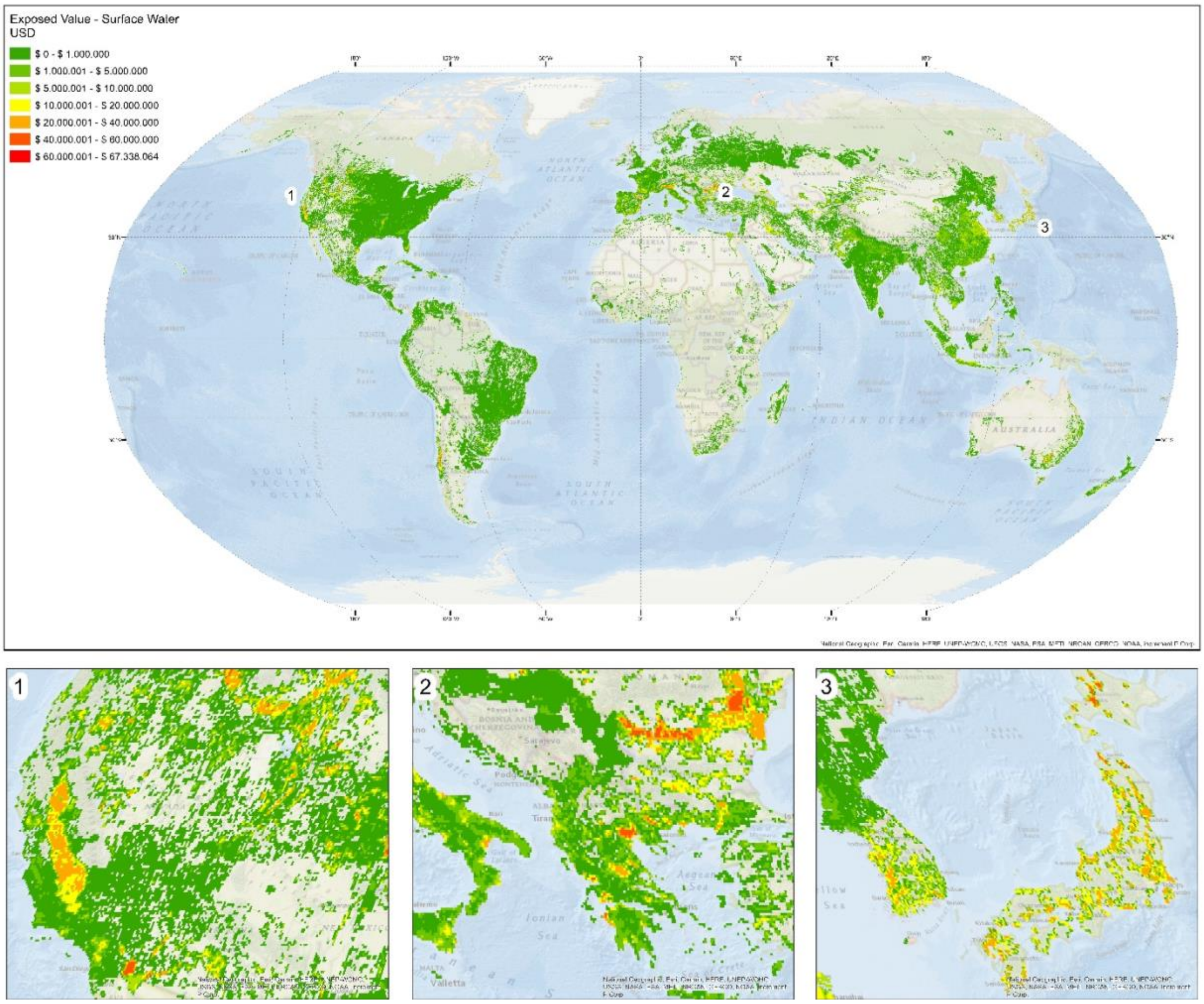

Figure 2.4. Exposed value of surface water-based irrigation infrastructure

Source: INGENIAR Risk Intelligence (2025)

The contrast between the two maps illustrates how the geography of water resources shapes the structure and global footprint of irrigation exposure. Groundwater systems dominate dry continental areas, and surface water systems are concentrated along major hydrological corridors. These general patterns and the detailed exposure data generated lay the groundwork for the next steps in the risk modelling.

2.2 Vulnerability Functions

A major achievement of the GIRI is the development of new vulnerability functions for different types of irrigation infrastructure. These build on and expand the number of existing GIRI vulnerability archetypes generated in 2023 and differentiate between the different irrigation systems discussed above. The different irrigation systems, and the many variations within each type, can be modeled through a set of elements and archetypes, which provide the basis for the generation of vulnerability functions for each (see figure 7).

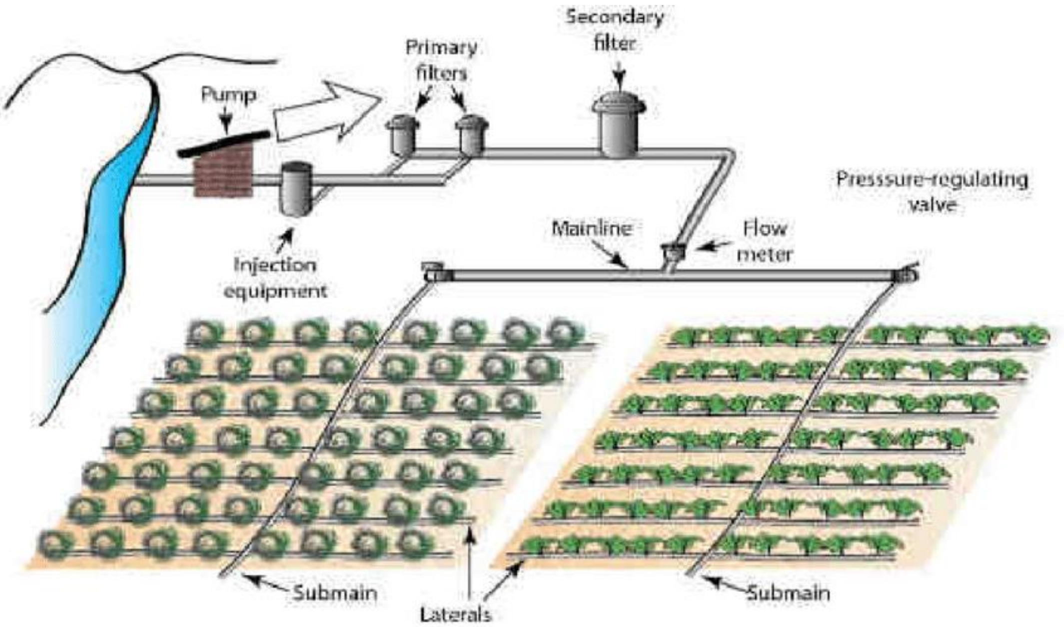

Figure 2.5. Main components of a drip irrigation system

Source: WFP (2018)

The vulnerability functions for the different components in an irrigation system were developed separately for each component and hazard. This was done to enable modelling of the full complexity of impact on a system, as each part will react differently to different effects of a particular hazard, such as ground acceleration, velocity, or displacement from earthquakes (see Figures 2.6 and 2.7).

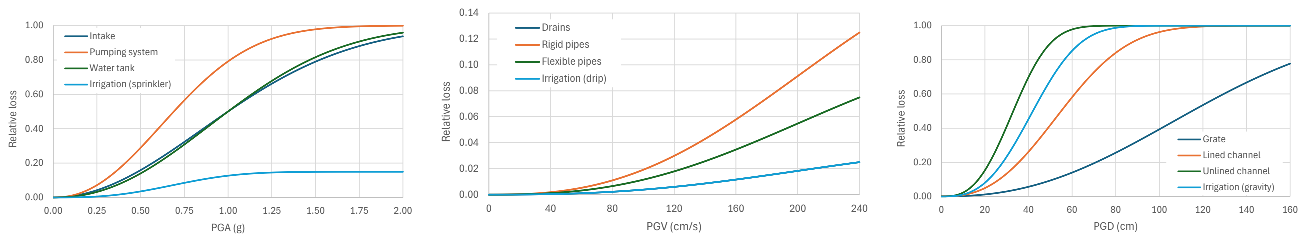

Figure 2.6. Vulnerability functions for irrigation system elements for earthquakes

Source: INGENIAR Risk Intelligence (2025)
Note: Intensity is from left to right: i) peak ground acceleration (PGA), ii) peak ground velocity (PGV), and iii) peak ground displacement (PGD).

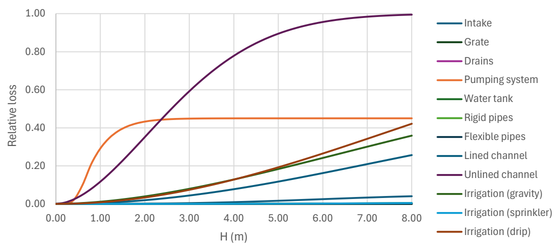

Figure 2.7. Vulnerability functions for irrigation system elements for floods

Source: INGENIAR Risk Intelligence (2025)
Note: Intensity is flood height.

2.3 Risk Results

The global risk to irrigation infrastructure from disasters is nearly $2 billion of AAL. Although it is a worldwide phenomenon, each region faces distinct hazard-specific challenges, along with varying climatic, tectonic, social, and economic conditions that influence infrastructure exposure and vulnerability. As a result, global AAL is not evenly distributed across the globe (see Figure 2.8).

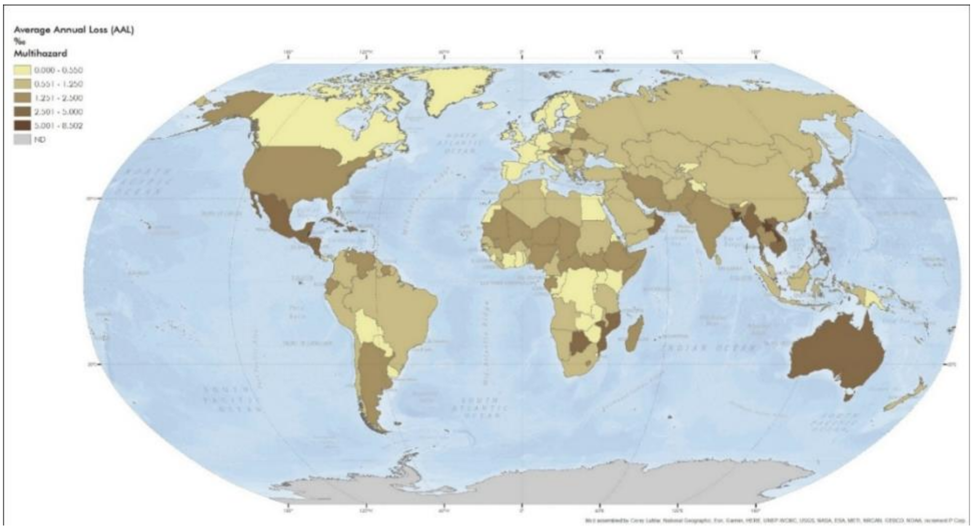

Figure 2.8. Multi-hazard AAL for irrigation systems, AAL by country in per mille

Source: INGENIAR Risk Intelligence (2025)

When considering the AAL values for irrigation infrastructure, it is important to remember that the replacement cost, which underlies the AAL metric, understates systemic importance of the direct loss. Disaster risk to irrigation infrastructure often looks small in economic terms compared with transport, energy, or housing assets, yet it carries outsized consequences for food security because irrigation is a critical “lever” in agricultural productivity and stability. Even relatively modest direct losses to canals, pumps, or diversion structures can disrupt crop water supply over large areas, amplifying impacts on yields, rural incomes, and food availability far beyond the replacement cost of the damaged assets.

Tropical and subtropical developing countries face the highest overall risk, indicating that tropical climate instability and high dependence on surface irrigation contribute to systemic vulnerability. In absolute terms, countries with large-scale irrigation infrastructure and high capital investment in infrastructure assets will rank highest in disaster risk (see Figure 2.9). However, in terms of relative loss, small island states and several Asian low-income countries also show high levels of risk. For instance, Belize and Jamaica are most affected with relative AAL values above 8 per mille, mainly due to hurricane and flood-related risk. Similarly, Afghanistan, Bangladesh, Lao PDR (Lao People's Democratic Republic), and Vietnam also rank high in Asia, as do Chad, Mauritius, and Sudan in Africa.

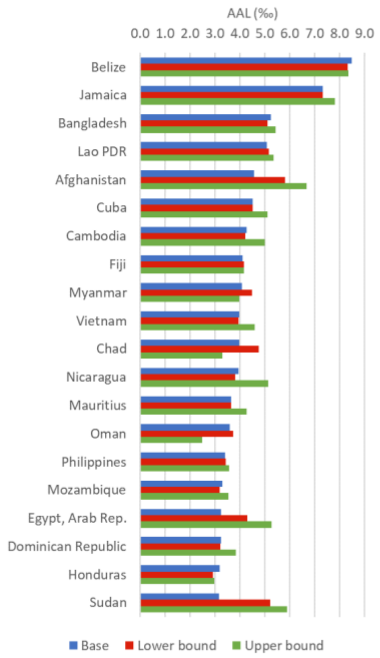

Figure 2.9. Top 20 countries, multi-hazard AAL

Source: INGENIAR Risk Intelligence (2025)

2.3.1 Regional Perspectives

The highest aggregated risk to irrigation infrastructure across all hazards is concentrated in South and Southeast Asia, Central America, and eastern Africa. These regions share the common challenge of multiple hazards, including floods, tropical cyclones, and heat stress.

South and Southeast Asia are the regions with most irrigated area as a percentage of total agricultural production areas globally. Bangladesh, India, Thailand, and Vietnam are particularly exposed due to large areas of exposed irrigation infrastructure. They also face high levels of hazard risk from monsoon floods, droughts, and cyclones, and struggle with large, ageing canal systems, as in Pakistan and India. In these countries, the combined AAL values for different hazards exceed 5 per mille, i.e., 0.5 percent of the total value of irrigation infrastructure assets. Although it may seem minor, this constitutes a substantial loss because irrigation is vital for food security and highlights these countries as global hotspots of irrigation risk (see Section 3).

For example, the 2022 monsoon floods in Pakistan inundated one-third of the country and damaged over 13,000 km of irrigation canals, distributaries, and watercourses in Sindh and Punjab. The flooding breached embankments of major irrigation systems, such as the Sukkur and Guddu barrage command areas, and destroyed pumping stations. This damage resulted in significant losses in rice and cotton production across Pakistan and parts of northwest India that rely on interconnected, often ageing and difficult to maintain, irrigation systems (Nazir et al., 2025).

The Pacific region, too, faces potentially localized losses with larger implications for food security. Australia, despite high levels of irrigated agricultural production, has comparatively low overall irrigation risk. However, even highly localized but severe disasters can cause large losses, as seen in late 2022 and early 2023. Exceptionally intense rainfall caused major flooding in the Murray–Darling Basin of southeastern Australia. Over 2,000 agricultural pumps were submerged or damaged, channel linings were breached, and irrigated horticulture (mainly almond orchards and vineyards) sustained significant losses (Colloff et al., 2024). Since Australia has high-value irrigated agriculture with concentrated assets, even localized events result in high loss intensity per unit of exposure.

In sub-Saharan Africa, the share of irrigated land in total cultivated land is low (Nhamo et al., 2024). However, the region faces significant risks because of its high vulnerability to drought, power outages, and cyclones. Further, widespread small-scale farming and dependence on national food imports influence food availability, prices, and consequently, food security. In 2019, Cyclone Idai brought extreme flooding to river valleys in Mozambique and Malawi, destroying smallholder irrigation schemes, lifting off diversion weirs, and washing away pumps and pipes used for community-managed systems (Nhamo & Chikodzi, 2021). Electricity outages crippled larger pump-fed schemes for weeks. Although the actual irrigated area is small, the region’s high vulnerability to drought, unreliable power, and cyclone exposure meant that infrastructure losses rapidly translated into reduced food availability and higher market prices for key staples.

In the Middle East and North Africa, water scarcity leads to a high dependence on irrigation, with infrastructure systems vulnerable to heat stress and droughts, as well as to groundwater depletion and salinity intrusion (Al-Taani et al., 2021). This intensifies existing pressures on the water–energy–food security nexus in the region. Domestic cereal output, an important indicator of food security in the region, can be affected, leading to increased reliance on food imports. Between 2017 and 2018, Iraq and Syria experienced a severe and prolonged drought that lowered water levels in the Tigris and Euphrates rivers. This decline reduced reservoir capacity and left irrigation systems in affected regions vulnerable to intense heat stress and salinity intrusion (Abdelmohsen et al., 2022). Canals in southern Iraq suffered reduced flow from the Euphrates, and pumping stations along the river had to be temporarily shut down because salinity exceeded thresholds for agricultural use. The drought sharply reduced the region’s domestic wheat production, forcing higher-than-normal cereal imports and intensifying the water–energy–food security pressures characteristic of the region.

In Central Asia, the Soviet Union’s substantial investments in irrigation have resulted in infrastructure that exists even in challenging terrain, though much of it is now ageing (Dankova et al., 2022). In addition to earthquakes, floods, and droughts, the region’s irrigation infrastructure faces significant risks. In 2016, heavy rain and snowmelt triggered floods and mudslides that damaged irrigation systems in Tajikistan (Gaforzoda & Yuldachev, 2023). These were Soviet-era canal systems and pumping stations that served large agricultural areas across difficult terrain and were highly vulnerable to seismic risk and washouts.

In Latin America, large-scale irrigation for commercial agriculture is mainly concentrated in Mexico, Brazil, Chile, and Peru, all of which face significant flood, drought, and hurricane risk (Rodríguez et al., 2022). Regional food exports, particularly soybeans and fruit, are vulnerable to infrastructure damage, where losses can trigger significant food price spikes that ripple through local and regional economies. Extreme rainfall linked to a coastal El Niño in 2017 caused widespread flooding across northern Peru. Major irrigation systems, including the Chavimochic and Puyango-Tumbes schemes, suffered canal breaches, sedimentation, and pump damage (Motschmann, 2021). As Peru and neighbouring countries export high-value irrigated crops such as grapes, blueberries, and asparagus, the damage reduced export volumes and caused temporary regional price volatility.

In higher-income countries of North America and Europe, highly developed irrigation systems often exhibit greater resilience but are not immune to losses. In central and southern Europe, risks to irrigation systems include extreme heat and floods; in the United States, it is drought and resulting water scarcity. Impacts on productivity from such risks can affect global commodity markets, particularly those for large-scale crop exports. Europe's 2022 drought—its worst in more than 500 years—depleted rivers such as the Po (Italy), Ebro (Spain), and Danube, severely restricting irrigation withdrawals (Biella et al., 2025). In the Po valley alone, over half of irrigated maize and rice farmland was affected, with canals running dry and pumping restrictions imposed. Even though Europe's irrigation systems are technologically advanced, they proved highly vulnerable to extreme heat and water scarcity, leading to major reductions in agricultural production and contributing to global price pressures.

2.3.2 Hazard-specific Impacts

Floods are among the most significant hazards for irrigation systems, costing almost $1 billion of AAL globally. Riverine floods can overtop or breach embankments, damage diversion weirs, or wash out canal headworks. Flash floods in smaller catchments can overwhelm minor irrigation tanks and culverts, damaging rural distribution systems. Coastal floods and storm surges can inundate low-lying irrigation command areas, contaminating soils and irrigation canals with saline water. Flooding not only damages infrastructure but also interrupts water distribution for weeks or months, affecting cropping calendars. For example, in South Asia, monsoon floods regularly damage canal linings and outlets, resulting in significant repair costs.

Food risk to irrigation infrastructure is widespread across the globe, particularly in South and Southeast Asia, the Pacific, parts of sub-Saharan Africa, Europe, and Latin America (see Figure 2.10).

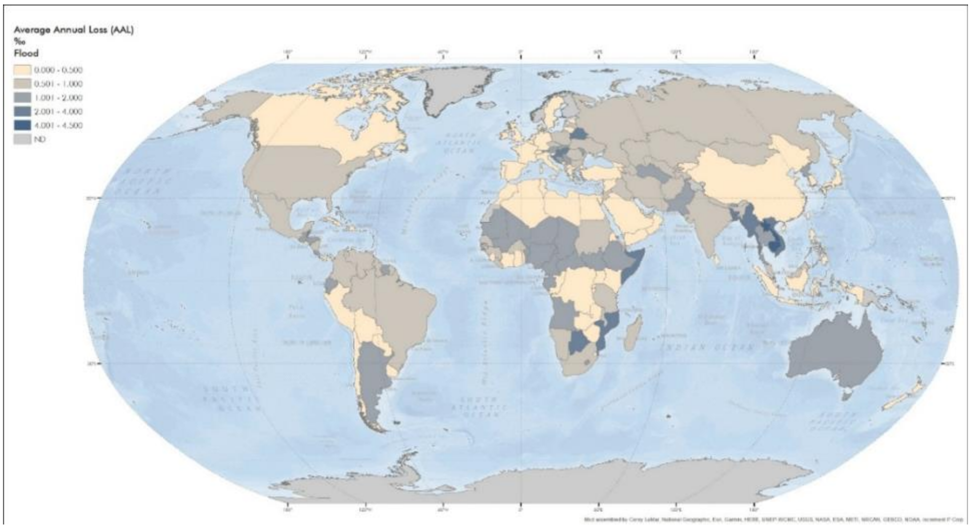

Figure 2.10. Flood risk for irrigation systems, AAL by country in per mille

Source: INGENIAR Risk Intelligence (2025)

Globally, floods also present the highest risk to irrigation systems under future climate scenarios. Under both low- and high-band scenarios, AAL from floods increases markedly in South and Southeast Asia, especially in Bangladesh, Vietnam, and Myanmar, as well as in eastern and southern Africa, notably Somalia and Mozambique. Higher-bound climate scenarios (SSP5–8.5) dramatically increased risk in tropical regions: AAL is estimated to increase by more than 50 percent under these scenarios, highlighting the sensitivity of irrigation systems to more extreme precipitation and resulting flooding.

In Europe and North America, comparatively, AAL from floods remains moderate, even under future scenarios. However, it also remains geographically widespread. This suggests exposure to large-scale, but overall more resilient, infrastructure.

Tropical cyclones present another significant risk to irrigation infrastructure. Storm surges can destroy pumping stations, while strong winds damage power lines that supply irrigation pumps. In 2019, Cyclone Idai inundated irrigation perimeters, damaging canals and water control gates in Mozambique, with dramatic impacts for the country's food production and subsequent food security.

Globally, expected losses are concentrated in coastal areas of Southeast Asia, the western Pacific, and the Caribbean (see Figure 2.11).

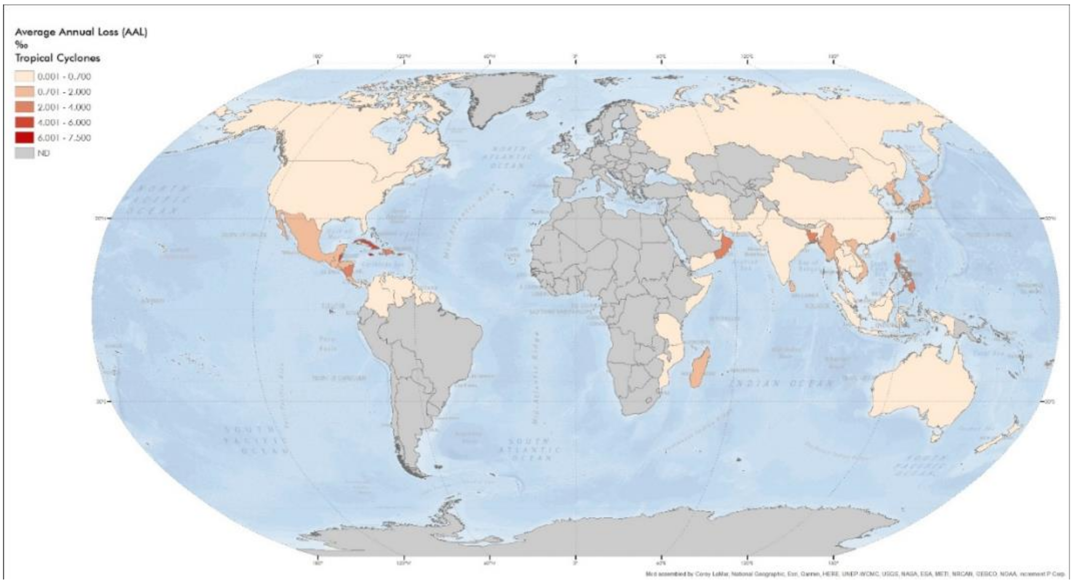

Figure 2.11. Tropical cyclone risk for irrigation systems, AAL by country in per mille

Source: INGENIAR Risk Intelligence (2025)

Under the upper-bound climate scenario, cyclone-related AAL increases sharply in Japan, the Philippines, Mexico, and the Gulf of Mexico region, reaching up to 7 per mille—or 0.7 percent—in highly exposed coastal systems. These losses are incurred from direct wind damage and surge effects on pumping and distribution infrastructure.

Large dams, barrages, and canal embankments are vulnerable to earthquakes, landslides, and soil liquefaction. A strong seismic event can cause structural failure of dam walls. It can trigger landslides into reservoirs, creating overtopping waves, and develop cracks or displacements in canal linings and aqueducts, disrupting water flows.

Examples include earthquake damage to irrigation canals in Nepal (2015) and the risks identified in seismically active regions of Central Asia and South America.

Japan, Chile, Iran, Turkey, and Central America face the highest earthquake risk, as irrigation systems intersect with active fault lines and areas of high seismic activity. While AAL values rarely exceed 1 per mille, they do present a significant risk. This is particularly the case in regions with extensive, rigidly built irrigation infrastructure, such as Iran and Mexico. Concrete and earthen components of irrigation systems in these countries are vulnerable to tremors and disruption to water conveyance systems that traverse unstable terrain (see Figure 2.12).

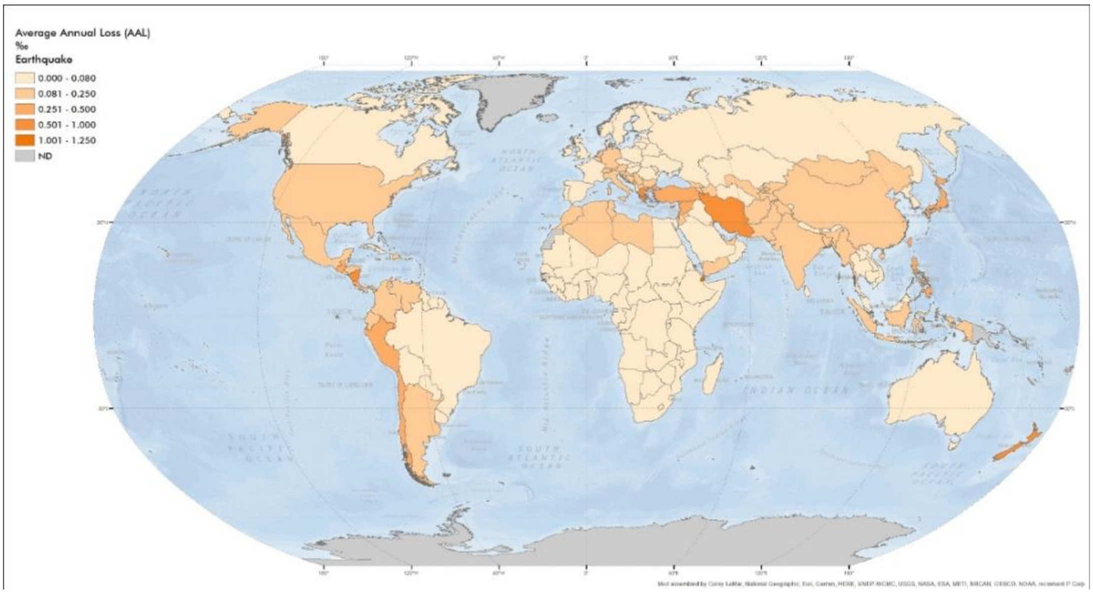

Figure 2.12. Earthquake risk to irrigation infrastructure, AAL by country in per mille

Source: INGENIAR Risk Intelligence (2025)

Risk to irrigation infrastructure from heat and cold waves is also widespread. In particular, rising average temperatures and sustained heat waves in North Africa and the Middle East present challenges to irrigation systems, but Mexico and several countries in South Asia and East Africa are also not spared (see Figure 2.13).

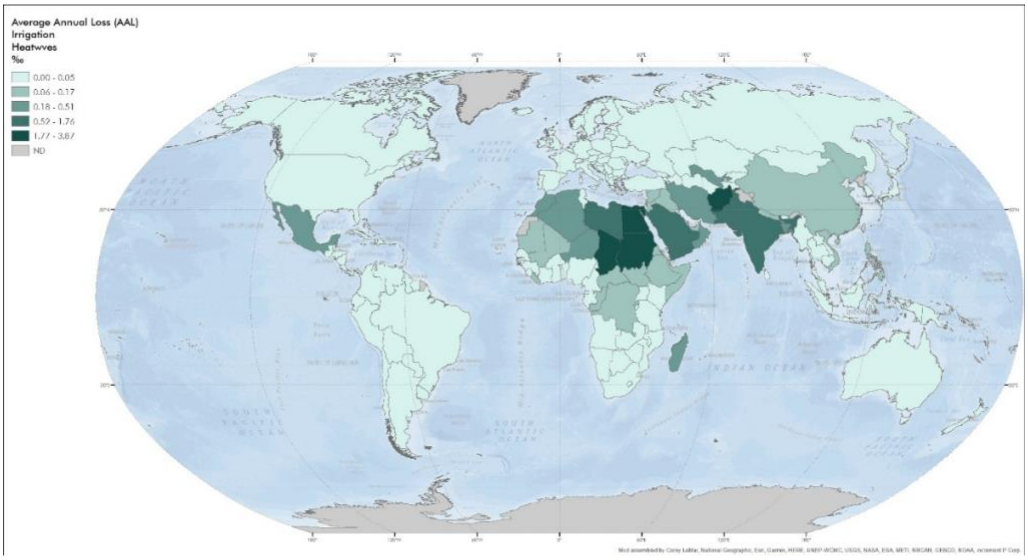

Figure 2.13: Heatwave risk for irrigation systems, AAL by country per mile

Source: INGENIAR Risk Intelligence (2025)

The highest AAL values, above 1 per mille, can be found in Chad, Egypt and Sudan, and in Afghanistan, Pakistan, as well as northern India. In these countries and regions, irrigation systems face compound stress from thermal degradation, reduced water availability, and operational strain on pumping infrastructure. The spatial coherence with arid and semi-arid zones underscores the close link between climatic exposure and irrigation dependency.

Cold waves and low temperature extremes are a significant risk to irrigation infrastructure across the northern hemisphere, in particular in China, Kazakhstan, Russia, Pakistan, and several countries in Central Asia, Europe and the Middle East (see figure 16).

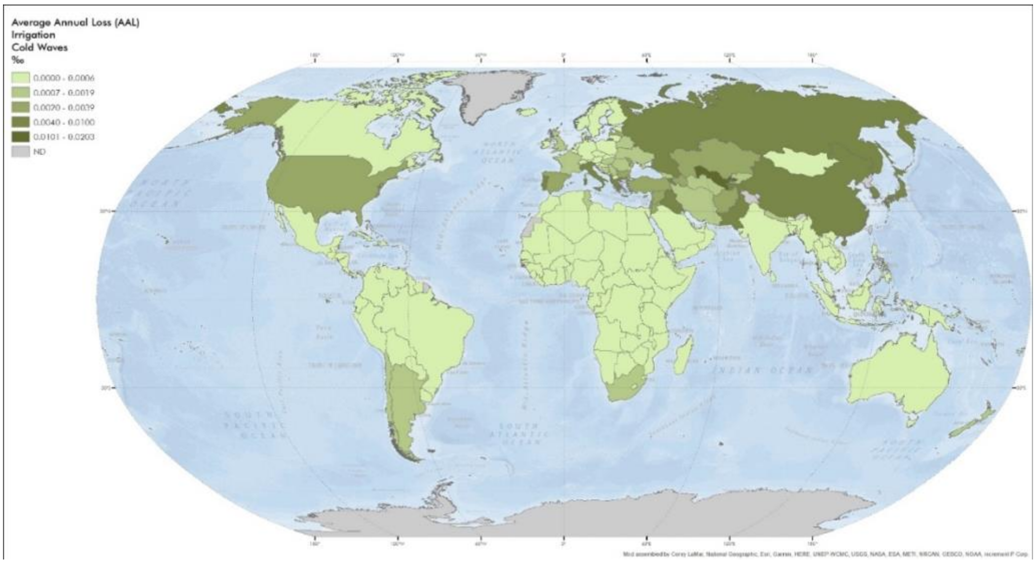

Figure 2.14. Cold wave risk for irrigation systems, AAL by country in per mille

Source: INGENIAR Risk Intelligence (2025)

Although magnitudes stay below 0.02 per mille, the extensive geographical coverage suggests a potential risk of operational disruptions from irrigation network freezing. Specific countries in the Americas also need to account for the risk to their irrigation systems posed by sustained low temperatures. Argentina and the northern United States, in particular, show measurable exposure, indicating that even moderate cold wave intensity can impact extensive irrigation infrastructure in temperate agricultural belts.

The risk from a Tsunami is highly concentrated, particularly along Japan and Indonesia's coastlines, but also in selected countries of the Mediterranean region, the Middle East, and North Africa (see Figure 2.15). These countries combine high seismic activity with dense irrigation and aquaculture systems near low-lying coastal plains. The estimated AAL rarely exceeds 0.5 per mille, yet the concentration of exposure in floodplains and deltas suggests potentially severe localized losses during extreme events.

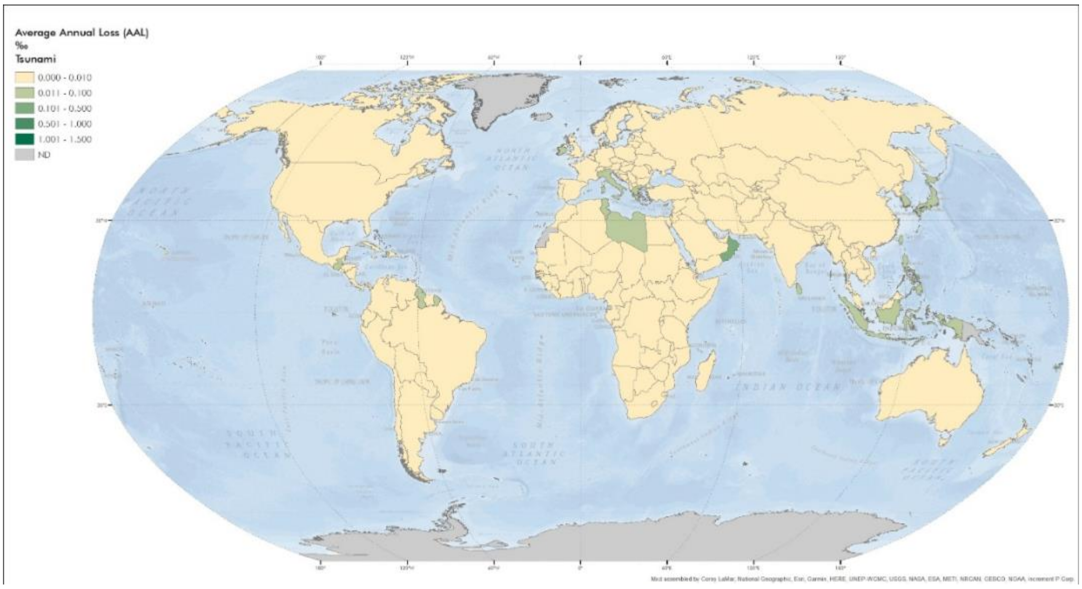

Figure 2.15. Tsunami risk for irrigation systems, AAL per country in per mille

Source: INGENIAR Risk Intelligence (2025)

2.3.3 Droughts and Slow-onset Events

Even without sudden disasters, irrigation systems face the risk of being affected by slow-onset events, such as sedimentation, which reduce reservoir capacity and undermine long-term irrigation reliability. Further, erosion of canal banks and embankments increases failure risks during floods and, in combination with ageing dams, can pose safety risks, especially where monitoring and maintenance are inadequate. Catastrophic dam failures, though rare, have devastating impacts on food security in irrigated valleys.

In coastal and arid areas, salinity intrusion and soil salinization undermine irrigation effectiveness. Disasters such as storm surges or prolonged droughts exacerbate salinity by allowing seawater to encroach into aquifers and canals. Poor drainage after floods can also cause salt accumulation in soils, reducing long-term productivity.

Irrigation is meant to buffer against rainfall variability, yet droughts still threaten irrigation infrastructure and services. Reduced reservoir inflows decrease water availability for canals, forcing cutbacks in irrigation deliveries. Groundwater-fed schemes face declining aquifers, with pumping costs rising or wells drying up. Drought can also trigger conflicts among competing water users, including urban supply, hydropower, and agriculture. The 2015–2016 El Niño event highlighted this vulnerability: several large Asian irrigation systems reported dramatic water shortages, leading to rice import surges and stressed public budgets (Sekhar, 2018).

2.4 Multi-hazard Risk Trends Under Future Scenarios of Climate Change

Climate change intensifies the stakes by increasing both the hazard to infrastructure and agriculture's reliance on reliable water management. More frequent and intense droughts, floods, and storms threaten to damage irrigation assets more often, shorten their effective lifetimes, and increase maintenance needs. At the same time, shifting precipitation patterns and more erratic rainfall make irrigation a cornerstone of climate adaptation, enabling farmers to buffer yield variability and reduce exposure to rainfall shocks. It is important to understand, however, that irrigation systems are not just affected by climate change, but may also contribute to the global carbon footprint and thereby to global warming potential (Karimi et al., 2012). In addition, population growth and, importantly, demand growth associated with GDP and income growth will significantly increase the exposure of irrigation infrastructure worldwide.

Consequently, it is possible to envisage a triple-risk scenario in the context of climate change, in which damage to irrigation infrastructure accelerates due to the changes in hazard intensity and frequency The newly developing infrastructure potentially increases the carbon footprint, further accelerating climate change. Consequently, the rapidly growing demand for irrigation significantly increases the exposure footprint and strains resources for the maintenance and rehabilitation of existing infrastructure, thereby increasing vulnerability. For irrigation infrastructure, the increase in food demand is an important factor to consider, and population growth may not be the only driver. For instance, it has been found that growth in food demand (and thus in irrigated agriculture) is linked to per capita demand growth associated with rising incomes (Fukase & Martin, 2020).

However, the specific risks to irrigation infrastructure associated with the negative impacts of climate change alone are not insignificant. They range from increased hydrological variability resulting in more intense floods and droughts, to sea-level rise associated with greater salinity risks for coastal irrigation, compound risks where simultaneous drought and heat stress affect irrigation demand and the physical integrity of infrastructure assets. Additionally, glacier retreat impacts water supply for irrigation, especially in regions such as Central Asia, the Andes in South America, and the Himalayas in South Asia.

The GIRI model provides three estimates for each country (a baseline, a lower-bound estimate, and an upper-bound estimate). These together demonstrate each nation's sensitivity to climate change and illustrate how losses could increase if temperatures rise more rapidly than projected. When considering the combined risks from all major hazards, the anticipated losses across several countries are substantial but do not increase linearly with emissions scenarios (see Figure 2.16).

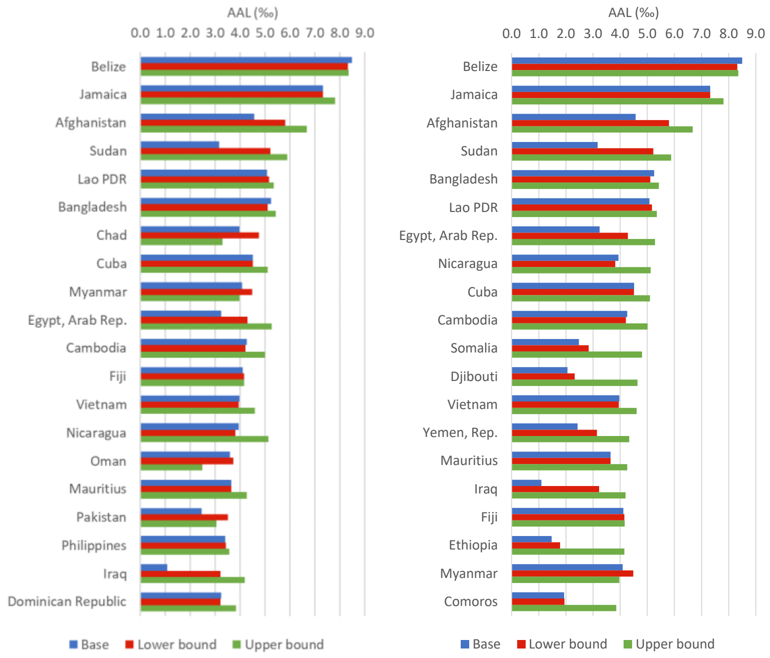

Figure 2.16. Top 20 countries ranked under lower-bound (left) and upper-bound emissions scenarios (right)

Source: INGENIAR Risk Intelligence (2025)

Under future climate scenarios, risk remains highest in tropical and subtropical developing countries, where hydrometeorological variability and hazards combine with high dependence on irrigated agriculture. This leads to high exposure and vulnerability, depending on irrigation type.

Under future climate change, many countries could experience much greater losses to their irrigation systems, directly reducing their agricultural output.

In a low-emissions future (the SSP1–2.6 scenario), the countries with the highest expected AALs remain largely unchanged. Belize, Jamaica, and Afghanistan remain at the top of the list. A few countries, such as Sudan, Chad, and Egypt, move higher in the ranking because their risks shift from mainly coastal flooding to a greater risk of damage from extreme heat. Some countries, such as Lao PDR, Bangladesh, and Myanmar, consistently rank among the top ten. This shows that even with limited global warming, countries with large floodplain irrigation systems will continue to face major risks. Afghanistan and Vietnam also experience high annual losses, mainly because they depend heavily on large irrigation networks built on floodplains and rely on seasonal monsoon rains, which are increasingly unpredictable.

Adaptation measures can help reduce losses, but they cannot completely prevent them in these heavily irrigated areas. New additions to the high-risk list, such as Pakistan and Iraq, show how even small increases in heat and water scarcity can strongly affect irrigation in dry regions.

In a high-emissions future (the SSP5–8.5 scenario), risk to irrigation infrastructure spreads across a much larger set of countries. Many more arid and semi-arid countries in Africa and the Middle East enter the high-risk group. While Belize and Jamaica remain highly exposed, countries such as Afghanistan, Sudan, and Egypt rise to the top of the list. New additions—Somalia, Djibouti, Ethiopia, and Yemen—show how rising temperatures and water shortages can quickly turn small water volumes into severe floods or droughts. In these countries, expected annual losses range from 0.5 to 0.8% of asset value, even though their irrigation systems are smaller. The severe climate amplifies the impact of every shock. In contrast, humid tropical countries such as Vietnam, Cambodia, and Fiji retain relatively stable risk levels. They still face floods and storms, but climate change increases risk most dramatically in already dry, water-stressed regions.

While some countries face high risk under all climate scenarios, for some, the severity of future climate change matters enormously. Egypt is a case in point: under high-emissions conditions, Egypt's expected losses rise sharply, showing how sensitive some countries are to increases in heat and water scarcity.

Overall, the low-emission scenario shows two main trends directly related to water scarcity and abundance. First, countries that are already highly exposed to floods continue to face heavy losses (see Figure 2.17). Secondly, countries that already face water scarcity may start to feel dramatically increased pressure from climate-related water stress even under future low-emissions scenarios.

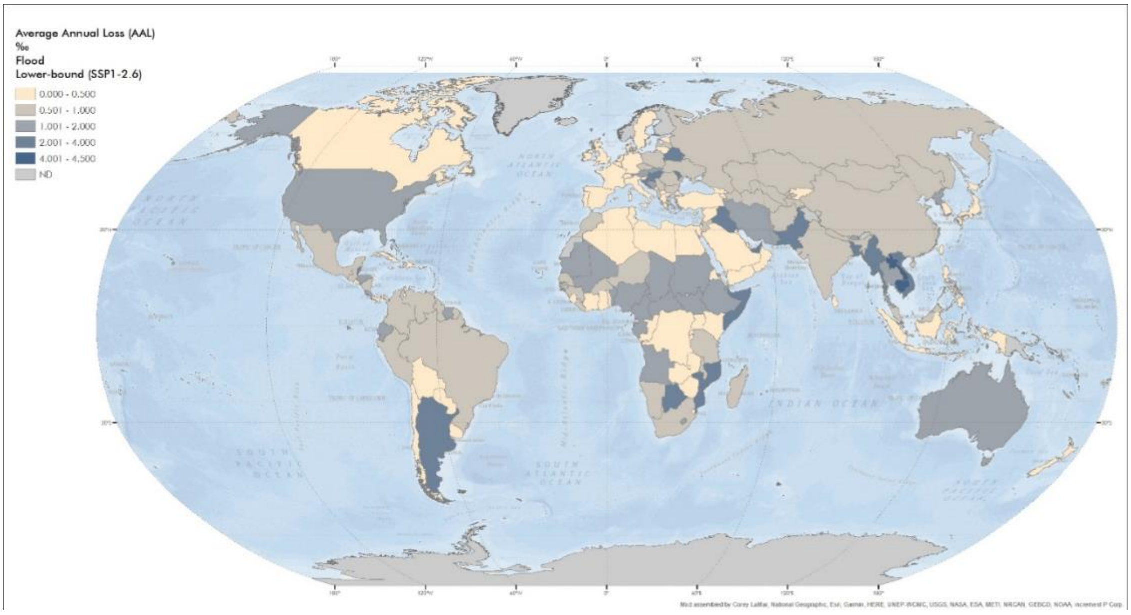

Figure 2.17. Global map of flood AAL (‰) by country for irrigation systems. Climate lower-bound

Source: INGENIAR Risk Intelligence (2025)

Overall, the results of the probabilistic modelling show that even small increases in global temperature can lead to much larger-than-expected losses for irrigation and other infrastructure. However, the relationship is not linear: a small rise in temperature can cause a big jump in damage, especially under the high-emissions scenario (SSP5–8.5). In this high-emissions pathway, heatwaves become longer and more intense. Countries that are already close to their limits—where heat regularly stresses crops, equipment, or water systems—may see risks increase very sharply.

3 Implications for Food Security

Irrigation infrastructure underpins a large share of the world's agricultural production. While only about 20 percent of cultivated land is irrigated, it contributes more than 40 per cent of global food output (FAO 2021).[3] This disproportionate role makes irrigation schemes—dams, reservoirs, canals, pumping systems, and distribution networks—critical assets for sustaining food security, livelihoods, and rural economies.

There are significant regional differences, of course. In China, for example, irrigated agricultural areas already account for more than half of total arable land (World Bank, n.d.). In countries with such high dependency on irrigation for agricultural production and in regions with high risk of water stress and/or variability, irrigation infrastructure resilience is thus a key determinant of food security (see Figure 3.1).

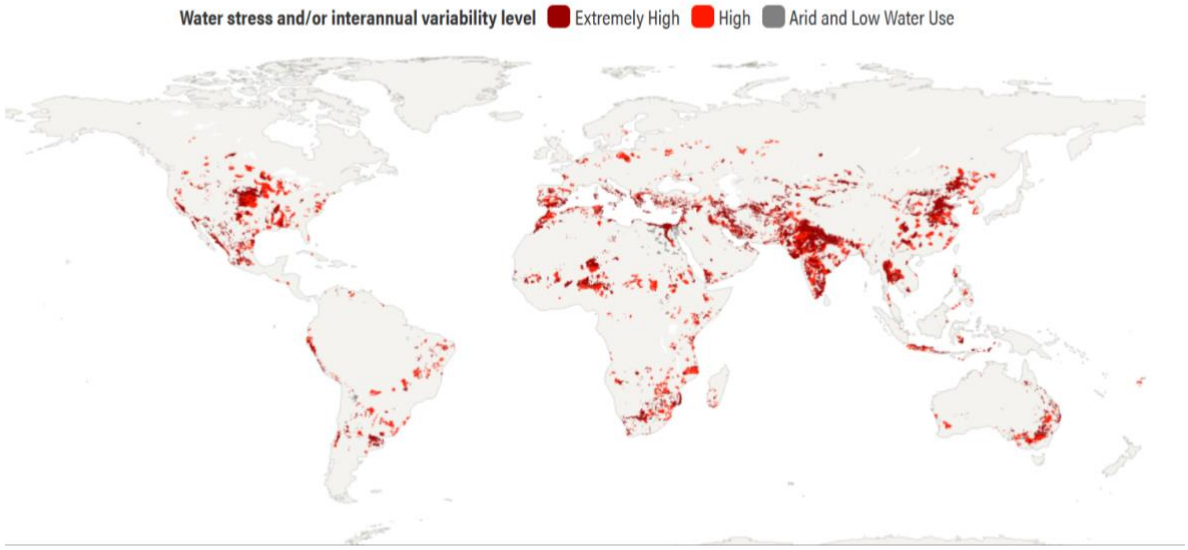

Figure 3.1. Global crop areas at high risk of water stress and/or variability

Source: WRI (n.d.)

Disaster impacts on food security can be direct, such as through direct loss of irrigation infrastructure, or indirect, through disruptions in labour demand and markets, but also through long-term changes to soil quality and land degradation (Gomiero 2016). Further, disasters can trigger broader regional price hikes and trade restrictions or volatility, further affecting food local and even national security, particularly in the context of increasingly negative impacts of climate change (FAO et al. 2025).

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[3] These percentages are estimates based on a range of sources. Relevant data for further analysis can be sourced from WRI (https://www.wri.org/applications/aqueduct/food); Eurostat (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_irrigation); and USDA (https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use).

Across the globe, substantial levels of irrigated agriculture are one important indicator for national food security (Hanjra & Qureshi, 2010). Globally, irrigated crops make up 34 percent of the world's total production by weight (see Figure 3.2).

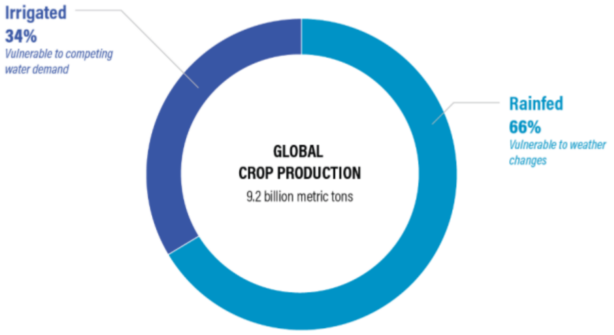

Figure 3.2. Irrigated versus rainfed crop production by weight

Source: WRI (n.d.)

Irrigation stabilizes yields, allows multiple cropping seasons, and supports high-value crops. Evidence from multiple regions shows that irrigation is closely linked to higher yields, cropping intensity, and resilience, which explains why physical damages with low replacement cost can translate into major food security impacts.

Studies reviewed for Turkey, for example, find that irrigation contributes between 50 and 80 percent of food production in some contexts and can nearly double yields compared with rainfed systems by extending the growing season and enabling more intensive cultivation (Sinar et al., 2018). In Indonesia's North Sumatra, one assessment estimated that irrigation systems account for roughly 65 percent of rice production, indicating that interruptions to irrigated water supply directly translate into large shortfalls in a staple food (Sinar et al., 2018).

Global analyses similarly emphasize that irrigation expansion and modernization can substantially increase crop output, support higher-value crop mixes, and reduce yield variability under climate stress, particularly in tropical regions (Rizzo et al., 2023). As irrigated agriculture supplies a disproportionate share of global calories and a large fraction of high-value crops relative to its share of cultivated land, damage to irrigation infrastructure can have system-wide consequences, including reduced exports from key 'breadbasket' regions and higher international prices.

Today, approximately 60 percent of irrigated crops are grown in regions that experience high or extremely high levels of water stress, making them vulnerable and contributing to increased competition over limited water resources (see Figure 3.3).

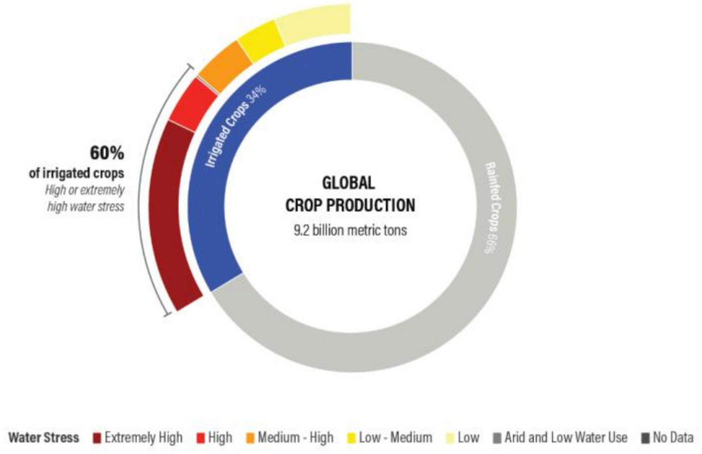

Figure 3.3. Percentage of irrigated crops (by weight) grown in regions of high or extremely high water stress

Source: WRI (n.d.)
Note: Water stress is considered 'high' if at least 40% of the local water supply is used to meet demands from farms, industries, power plants, and households (WRI, n.d.).

Most of the world's irrigated crops (by weight) are grown in a relatively small number of countries. Just 10 countries—Brazil, China, Egypt, India, Indonesia, Mexico, Pakistan, the United States, Thailand, and Vietnam—account for 72 percent of global production. They grow crops such as sugarcane, rice, wheat, vegetables, cotton, and maize, two-thirds of which face high to extremely high levels of water stress (see Figure 3.4).

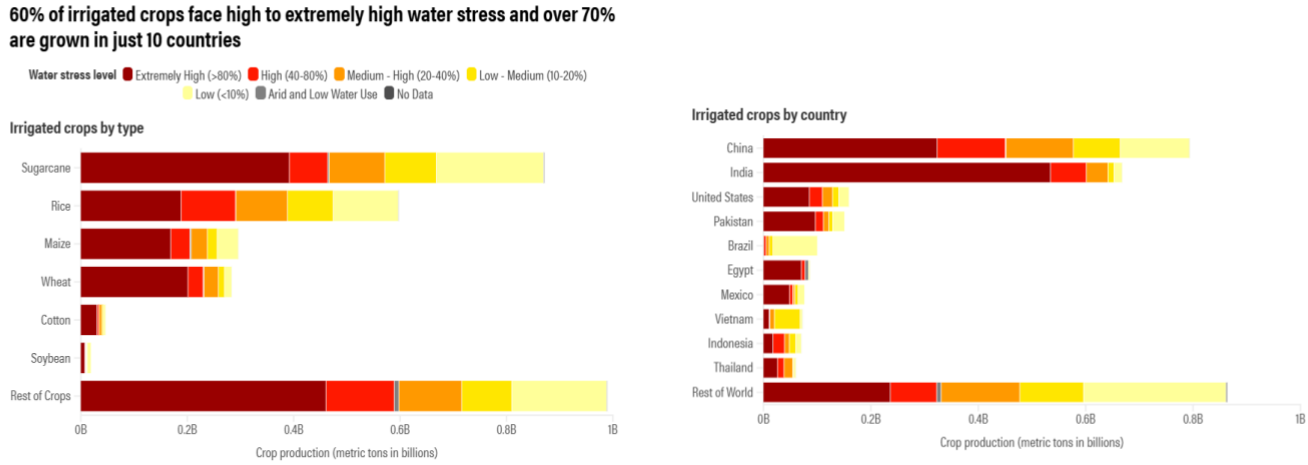

Figure 3.4: Crops facing water stress, by crop (left) and country (right)

Source: WRI (n.d.)

Direct loss of irrigated production occurs when irrigation infrastructure is disrupted and irrigated crops fail. When irrigated land is disproportionately productive, losses can be severe. A single flood event damaging irrigation infrastructure in a rice-producing valley may disrupt national food supplies (Li et al., 2025). Indirect effects can be mediated through input as well as output markets, with disasters affecting labour demand, fertilizer use, and marketing logistics. When damaged infrastructure results in reduced irrigation, investments in inputs such as fertilizers, pesticides, or labour-intensive weeding decline, lowering rural incomes. At the same time, reduced harvests increase market prices and volatility, further affecting food insecurity.

Disaster impacts and damage to irrigation infrastructure can also result in long-term declines in productivity and food security. Salinization, sedimentation, or unrepaired damage degrade land and water resources, leading to chronic productivity losses and undermining resilience to future shocks (FAO, 2023). Further, irrigation supports high-value crops, such as vegetables and fruits, which are essential for dietary diversity. Damage from disasters can reduce the availability and affordability of nutrient-rich foods, with implications for nutrition (Balgah et al., 2023).

Finally, countries that are major exporters of irrigated staples such as wheat, rice, or maize influence global markets. Disasters in such regions can trigger trade restrictions and price spikes, affecting food security elsewhere, reflecting national and global trade dependencies (Arreyndip, 2021; Hasegawa et al., 2022).

As a result, the flow of benefits over time vastly exceeds the structure’s capital cost. When a flood, cyclone, or earthquake damages an intake structure or collapses a main canal, the immediate repair bill might be modest. Still, the resulting interruption in water deliveries can affect thousands of hectares and multiple harvest cycles, resulting in losses several times the asset’s value.

FAO’s global assessments show that agriculture often absorbs nearly two-thirds of recorded disaster losses in developing countries when crops, livestock, and rural infrastructure are included. This shows that even small-scale rural assets sit at the centre of much larger production and livelihood systems (FAO, 2021; FAO, 2025). Irrigation is deeply embedded in these systems; thus, its failure produces cascading impacts: reduced output, income shocks, food price spikes, and heightened vulnerability among rural households and net food buyers. Further, reduced soil fertility increasing salinization or waterlogging after flood events and storms can also undermine the performance of irrigation schemes, even after repairs to direct physical damage to the infrastructure.

Irrigation’s role in food security is magnified by its spatial reach, where one infrastructure system serves many farms and sometimes vast tracts of fertile land. In large irrigation networks, upstream headworks often connect with downstream distributaries over tens or hundreds of kilometres; a single point of failure can compromise water deliveries to a wide command area. Depending on when in the planting cycle disasters strike, losses can increase exponentially, for example, during planting and critical growth stages (Shahbazi et al., 2025). An intake damaged shortly before the irrigation season may prevent planting altogether, leading to a complete loss of one or more harvests rather than a marginal reduction in yields (Yuan et al., 2025).

Rural communities may also lose collateral and creditworthiness if repeated infrastructure failures reduce expected yields, further constraining recovery and reinvestment (Liu et al., 2025; Mazur, 2023). These distributional effects mean that, in welfare terms, a unit of loss to irrigation-dependent production in such contexts has a larger impact than an equivalent loss in higher-income infrastructure sectors.

The socioeconomic profile of those who depend on irrigation may further help explain why low asset values can mask high disaster risk in terms of welfare and food security. Small-scale irrigated schemes in developing countries are often used by smallholder farmers and tenant cultivators whose livelihoods depend on subsistence agriculture, small-scale commercial farming, and seasonal employment. When disasters damage canals or pumping systems, affected households may face simultaneous losses of subsistence food production, wage income, and on-farm assets, leaving them with limited buffers to absorb shocks. Farmers may also respond to unreliable irrigation by pumping deeper for groundwater, buying emergency water, or switching to more resilient but lower-yielding practices, which raises per-unit production costs (Osewe et al., 2020). Higher costs and higher perceived risk are then passed through in the form of higher farm-gate and wholesale prices, especially for high-value or water-intensive crops.

Furthermore, because poor households typically spend a high proportion of their income on food, even modest local price increases triggered by regional production shortfalls can push them into acute food insecurity (Stehl et al., 2025; Awasthi, 2025). Irrigation failures tend to cause the largest and most sudden local price spikes in highly water-dependent staples such as rice, wheat, maize, sugar crops, cotton, or soybeans, as well as in short-cycle, perishable vegetables, especially tomatoes, onions, and potatoes (Shahbazi et al., 2025). Perishable, high-quality products (fresh vegetables, fruits, and some animal products) tend to experience faster and larger local price spikes because the short-run supply is very inelastic and markets are often tightly integrated. Staple grains with larger storage and broader trade networks may see slower, but still significant price rises if the irrigation failure is prolonged or hits major producing zones (see Figure 3.5).

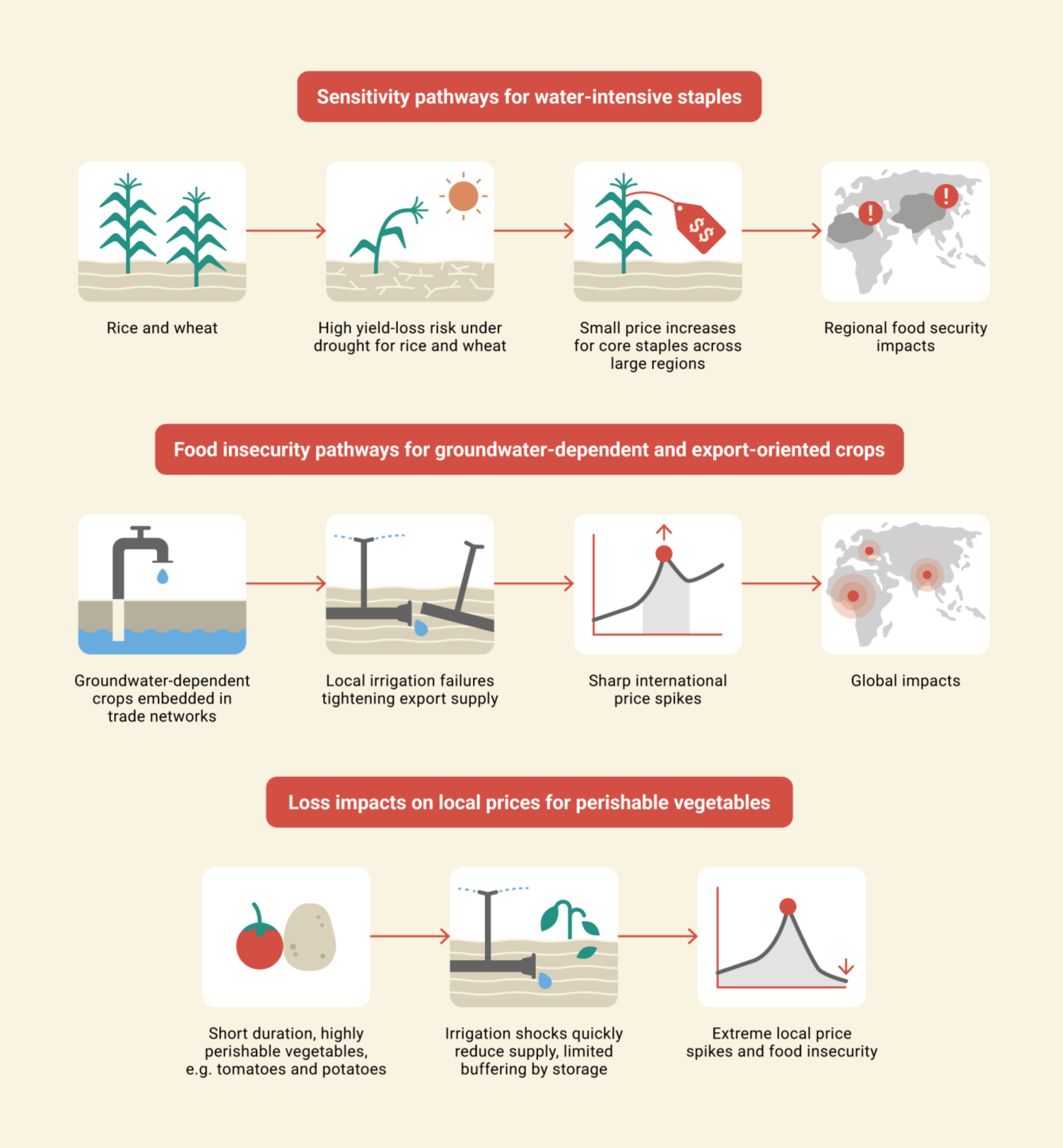

Figure 3.5. Crops with high sensitivity to price volatility linked to irrigation shortfalls

Source: Author's analysis

Disaster risks affect food security through multiple pathways, not all of which manifest in all countries. Thus, while the results from the GIRI model show that risk to irrigation infrastructure is a global phenomenon, the implications of such risk for food security are highly unequally distributed.

4 Investing in Resilience

As established in the previous sections, disaster risk to irrigation infrastructure appears low when measured solely by physical replacement cost. However, failures in irrigation systems during disasters result in cascading losses to food production and access that far exceed their monetary value. The apparent paradox—low replacement cost but high food security implications—has important implications for how associated disaster risk is managed. Therefore, sound analysis and pragmatic recommendations are needed to counter the low priority that irrigation systems currently face within disaster risk reduction strategies and programmes.

Investing in the resilience of irrigation infrastructure systems means investing in their capacity to absorb damage, respond to disruptions, and recover from loss. Therefore, significant future investment will be required across all levels and areas. However, particular attention should be given to improving assessments and technology, enabling financing, and strengthening institutions.

4.1 Investing in Front-line Knowledge and Technology

To strengthen the business case for investing in infrastructure resilience, better risk assessments and access to adequate technology are needed. Current loss metrics used in assessments are based on the cost of replacement. While these are a good proxy for asset damage, they do not represent the actual loss associated with lost production and subsequent impacts on food security. Methods must be developed to better understand the interactions between damage and downstream losses beyond engineering (Nikkels et al., 2019). This means incorporating the value of foregone production into models, along with knock-on price effects and livelihood impacts when irrigation fails. It consequently implies linking physical risk models for irrigation infrastructure with agricultural production models and food security indicators, including measures of nutritional adequacy and affordability for vulnerable groups (Nikkels et al., 2019).

More investment is also required in downscaled multi-hazard risk models for irrigation assets, as explored by INGENIAR Risk Intelligence and presented as part of the GIRI model in the 2025 report (CDRI, 2025). As the risk to the wide range of irrigation system types in a country can only ever be estimated by proxy, downscaling provides a more realistic and actionable set of metrics to guide disaster risk reduction efforts and climate-adjusted design standards (Wei et al., 2025; Esteves et al., 2023).

Further, broader infrastructure portfolio cost–benefit analysis for disaster risk reduction should account for the high benefit–cost ratios of protecting or upgrading irrigation systems, given their role in sustaining yields and stabilizing rural incomes under climate stress (Szott & Motamed, 2024). Investments in more robust canal linings, flood-resistant headworks, backup pumps, and improved drainage can have large payoffs by reducing the probability of catastrophic service interruptions, even if they add only marginally to the asset base's monetary value. However, to make the case for such investments, assessments of asset conditions are needed at a more granular scale and regularly updated, with data stored in local and national maintenance databases.

Finally, investing in technology is inevitable. While investments in new infrastructure will be needed, the effective upgrading of existing assets and investments in 'hardening' operational systems are essential and can be done at all levels: from reinforcement of canals and embankments in local irrigation systems, adopting digital solutions, or raising pump houses above flood levels (see Figure 4.1).

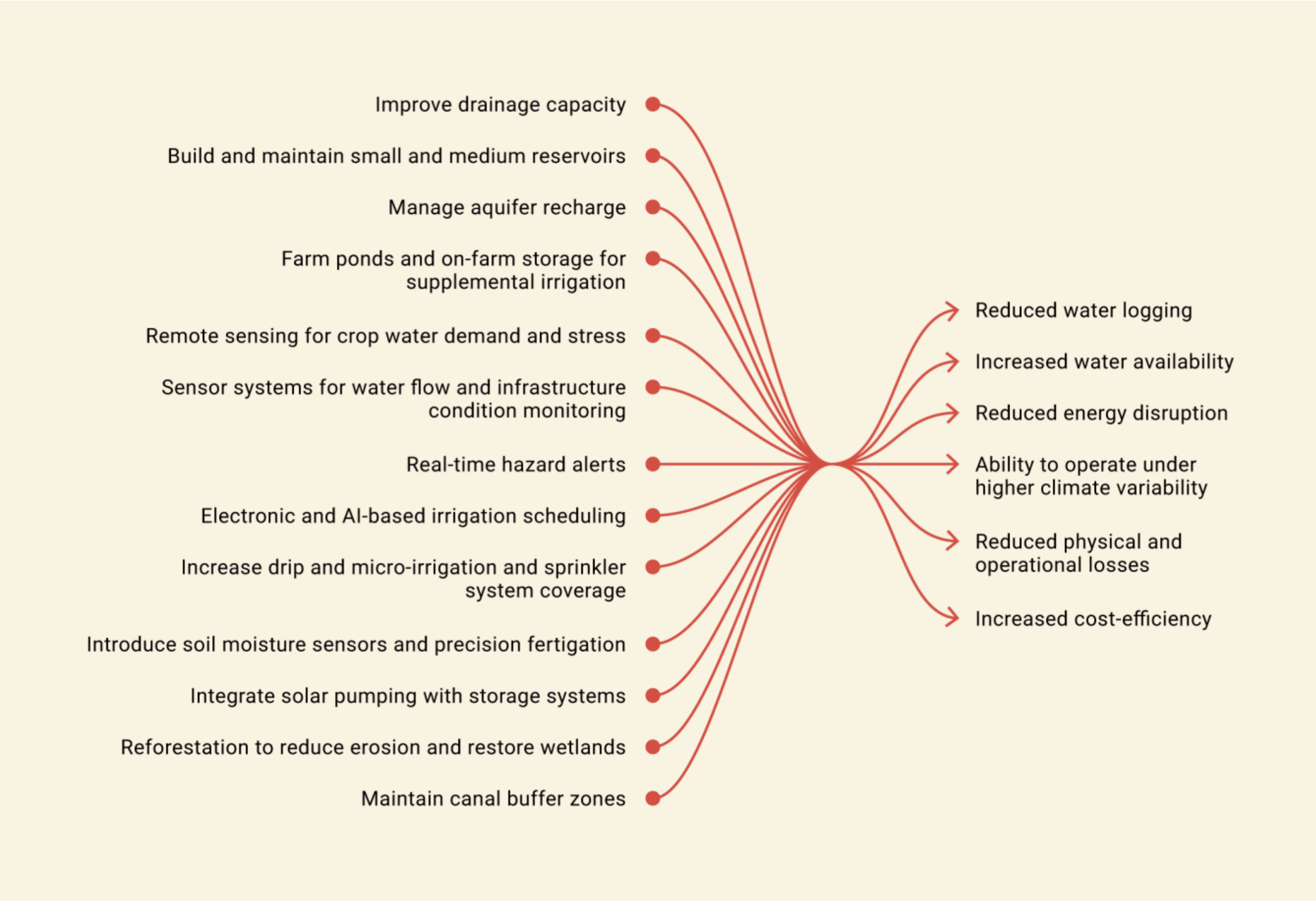

Figure 4.1. Technology investments in irrigation systems and resulting resilience benefits

Source: Author's analysis

Improving drainage capacity to reduce waterlogging is an important investment in any irrigation system, yet one that is commonly under-resourced with dramatic consequences during disasters. Increasing water storage and buffer capacity is equally important, and investments can be made at all levels, from building small reservoirs and community tanks to managing aquifer recharge at the level of a watershed (Gohar et al., 2015). In addition, a range of nature-based solutions, both traditionally employed as well as newly emerging, are proving to be cost-efficient and sustainable complements to hard infrastructure investments.

Maybe most importantly, and cost-effectively, real efficiency and disaster resilience gains for irrigation systems can be generated by focusing on improving general water management practices at community and watershed levels (Sikka et al., 2022).

4.2 Financing Strategies: Mobilizing Capital for Irrigation Infrastructure Resilience

The circumstances that justified and enabled large-scale public spending on irrigation in the latter half of the 20th century have shifted dramatically (Faurès et al., 2007). Today, with global food supplies relatively stable, population growth slowing down, real food prices continuing to fall, and other sectors increasingly competing for investment, there is no longer the same imperative to sustain past levels of irrigation funding. Beyond this common global trend, however, financing levels and available instruments for investing in irrigation infrastructure and its resilience vary significantly across countries and regions (Ward, 2010). Differences in fiscal space, institutional maturity, credit markets and rating systems, and private-sector depth fundamentally shape which financing mechanisms are viable in each context (Faurès et al., 2007).

Public financing remains the backbone of irrigation investment everywhere, but the composition and reliability of these resources differ sharply. In high-income countries, governments typically rely on direct budget allocations, which are often embedded in national infrastructure plans. Many of these countries also supplement public spending with fiscal incentives, such as tax credits for agribusinesses and related private-sector services, and subsidies that encourage on-farm adoption of water-efficient technologies, such as drip irrigation and sensor-driven systems.

Robust tax revenues and predictable budget cycles are a prerequisite for such public expenditure and incentive policies (Bhattarai et al., 2025). The fiscal constraints faced by low-income countries, however, create a very different financing environment. While governments may earmark resources for irrigation, these allocations are often modest relative to needs and must usually be blended with external funding. Many countries in this category, therefore, rely heavily on grants and concessional loans as well as on sovereign guarantees to make irrigation projects attractive to private investors or development partners. National irrigation or agricultural agencies usually play an operational role but often lack the capital required for large-scale resilience upgrades without donor involvement.

Beyond national budgets, subnational financing instruments also diverge by income level. In high-income countries, municipalities and districts frequently issue municipal or revenue bonds to rehabilitate irrigation systems or improve drought resilience (Close & Kleinman, 2025). In such schemes, repayment is secured through water tariffs or district-level charges. However, such mechanisms are generally absent or underdeveloped in low-income countries, where municipal debt markets are slim or non-existent, and where local governments face institutional, regulatory, or creditworthiness barriers. Instead, subnational projects in low-income countries tend to rely exclusively on donor-supported project finance.

In this context, specialized climate, water, and environmental funds also play a major role in financing resilience-oriented projects. Institutions such as the World Bank's International Development Association, regional banks such as the African and Asian Development Banks, and bilateral donors routinely provide concessional loans and thematically specialized grants for large-scale canal rehabilitation, drainage improvements, climate-smart irrigation systems, and community-based water management. Climate-oriented funds, such as the Green Climate Fund, the Adaptation Fund or the Global Environment Facility, also provide financing for projects that embed climate-resilience metrics or introduce modern technologies that would otherwise be unaffordable. In the context of disaster risk reduction, however, irrigation system resilience may not be a priority, neither for funding nor for the applying countries.

In the context of climate finance, high-income countries have begun to adopt green bonds and resilience bonds issued by government authorities or utility companies. Water credit trading has emerged as a new instrument that, in principle, enables reallocation during droughts and incentivizes investment in conservation technologies, thereby advancing disaster risk reduction objectives. However, the regulatory environment for these asset classes is not well established, and their potential is debated (Al-Yacoub, 2021). In addition, low-income countries—while also beginning to explore climate-resilience bonds—are typically dependent on donor funding or partial guarantees.

When it comes to private finance, the differences may be even more pronounced. In high-income countries, commercial banks provide credit to agribusinesses, irrigation districts, and water utilities for infrastructure upgrades. Increasingly, commercial debt is structured as green or sustainability-linked loans, in which interest rates are tied to achieving water-efficiency or climate-resilience outcomes (Brears, 2023; Radzewicz-Bak, 2024). Utility-scale irrigation modernization may be financed through long-term infrastructure loans from banks or infrastructure funds. Private equity and venture capital are also available for high-risk or large-scale investments in new technologies and large assets, with investors pursuing long-term horizons.

In low-income countries, however, commercial lending for irrigation is far more constrained (Khan et al., 2024). High interest rates, short loan tenors, limited collateral among farmers, and perceived risks around agricultural productivity make conventional bank lending rare except for large estates or export-oriented agribusinesses. Private investment tends to focus on early-stage enterprises, often only financing small-scale irrigation technologies or digital water services rather than larger assets or systems. In addition, this is often only possible when investors are assured of blended finance tools, first-loss capital options, and technical support from development institutions (Alaerts, 2019).

To address these challenges, the coming years will see an expansion of financing options for resilience investments in low-income countries (FAO, 2025). These can be created through deploying partial credit guarantees, de-risking private lending, and lowering overall financing costs, thereby increasing countries' access to affordable financing. For smaller farms, sustained public and finance-sector support for microfinance, microinsurance institutions, and impact investors can play a critical role, particularly for infrastructure upgrades and investments in new technologies such as solar pumps (Battarai et al., 2025). Public-private partnerships are already common practice in this regard, in both high- and low-income countries, but to succeed, they require strong regulatory frameworks and layered support. In addition, in the absence of water-tariff systems that are capable of supporting cost recovery, as found in many low-income countries, such partnerships frequently depend on additional public funding and sovereign risk guarantees to sustain a project over time (Leckie et al., 2021; Motta-Veiga, 2021).

Therefore, successful financing for resilient irrigation infrastructure depends on a mosaic of instruments spanning public expenditure, grants and concessional finance, private capital, and a range of partnerships. The divergence lies not in the types of instruments available—many are conceptually similar—but in the degree to which institutional capacity, credit markets, and fiscal space allow these tools to be mobilized. Therefore, in the long term, investments in the broader enabling environment are required to increase overall access to finance. This means stabilising public budgets and increasing tax revenues; introducing tiered water tariffs; reducing interest rates; developing more sophisticated private-sector financing instruments, particularly layered financing structures that can attract private investment; and growing domestic capital markets (Beecher, 2021; Gietema, 2022; Milton & Dellai, 2025). In addition, more insurance instruments that de-risk investments and also transfer disaster risk away from farmers and irrigation institutions, such as utility-level catastrophe bonds, sovereign risk pools, and parametric insurance schemes, are needed (Kambali & Panakaje, 2022; Machete & Marques, 2021).

4.3 Evolving Infrastructure Governance

Countries with strong institutional arrangements exhibit lower overall disaster vulnerability, and this is also true for irrigation infrastructure risk. Land and water rights, transparent allocation rules, pricing policies, and recharge regulations all contribute to lowering disaster losses.

Laws and legal reforms that are particularly important include those on land ownership and water-use rights (Parven et al., 2022). Establishing clear ownership and transparent, enforceable zoning regulations go hand in hand when it comes to initial investments in irrigation systems and the management of asset risks. Further, transparent water allocation rules within and between communities, districts, and regions are particularly important during dry seasons and when droughts lead to severe water stress. Similarly, harmonization of irrigation and flood control responsibilities must go hand in hand with formal or informal water-trading and shortage-sharing agreements. At the watershed level, an integrated planning process that covers water, energy, and agriculture is required to avoid conflicts, waste, and the abuse of water resources critical to irrigation systems (Brinkley et al., 2022; Kalogiannidis et al., 2023; Rasul et al., 2021).

This also means that the expansion of irrigation infrastructure should occur only in areas not affected by water scarcity (Mehta et al., 2024). While previous expansion of irrigated agriculture has significantly increased agricultural productivity, it has also led to overuse and depletion of freshwater resources. In the face of increasing demand (Schmitt & Rosa, 2024), more than 50 percent of irrigation expansion in the past decades has occurred in areas that were labelled as water-stressed in 2000 (see Figure 4.2).

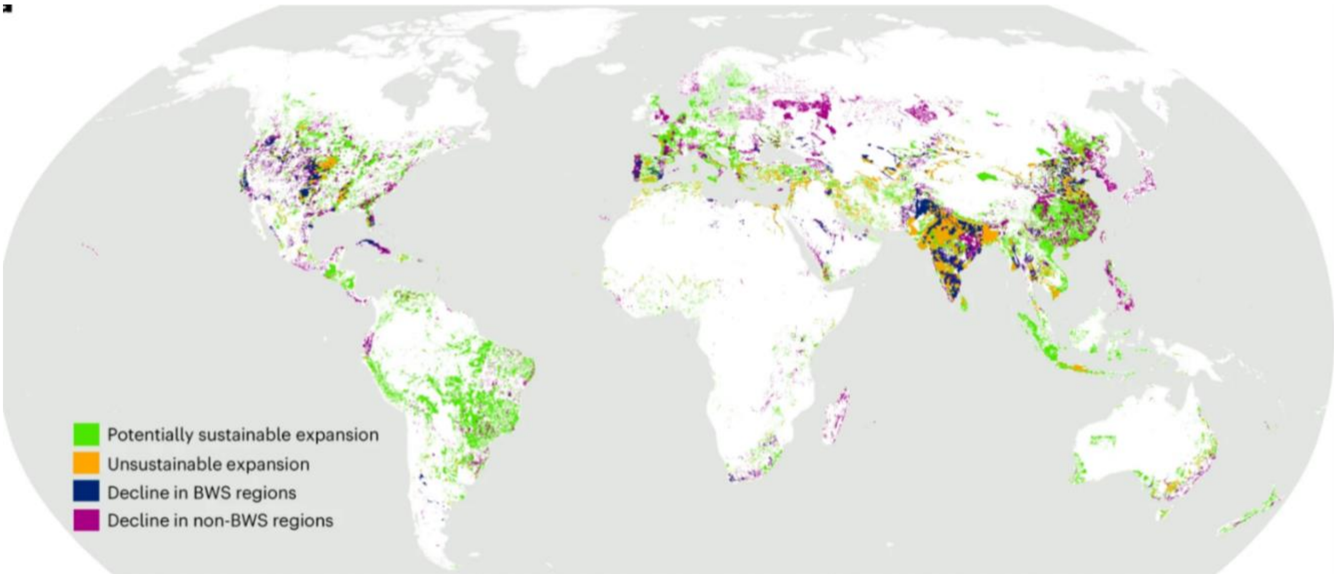

Figure 4.2. Sustainability of changes in the area equipped for irrigation in the 21st century

Source: Schmitt & Rosa (2024)

The need for future expansion of irrigation infrastructure depends heavily on future socioeconomic pathways but is expected to be particularly pronounced in the Middle East, North Africa, and South Asia (Palazzo et al., 2019). Therefore, for the future, sound assessments of where water is relatively abundant and how irrigated land has evolved (and can evolve) in a sustainable manner, particularly under conditions of future climate change, will be critical (Rosa et al., 2020).

But even without future expansion, many contexts today already require more effective management of both water resources and irrigation infrastructure systems. In this context, water user and farmer associations, as well as respected local governance mechanisms (formal and informal), play an important role (Gany et al., 2019; Suwanmaneepong et al., 2024; Engler et al., 2021; Wang & Chen, 2021). Where they are empowered to manage daily maintenance and water use, their capacity for successful conflict resolution during times of water stress and for rapid recovery after a disaster can be significant. Such local institutions can be responsible not just for oversight and maintenance of the irrigation system, but also for raising awareness of risks, preparedness, and emergency drills, and for coordinating direct responses during disasters, thereby reducing losses over time.

Finally, including irrigation in national disaster risk reduction strategies and climate change adaptation plans supports prioritizing irrigation infrastructure for agriculture in risk reduction and post-disaster recovery (Khan et al., 2021). In addition, national food security strategies should recognize the important role of irrigation and, ideally, be linked to disaster risk reduction and adaptation policies rather than remain separate, as is often the case (de Haen & Hemrich, 2007). Integrating provisions for early warning systems, irrigation system maintenance, and resilience investments into national and regional food security strategies should go hand in hand with the explicit integration of irrigation into national adaptation plans, investment strategies, and disaster risk reduction policies. Such mutual recognition and coordination at the strategic and policy levels would also go a long way toward enhancing the much-needed coordination among the environment, energy, and agriculture sectors.

5 Conclusion

Irrigation infrastructure occupies a relatively small and often undervalued niche within national infrastructure portfolios. Canals, pumps, gates, and embankments are inexpensive to build and maintain compared to megaprojects such as highways, power plants, or major water treatment facilities. Since these systems are built with simpler materials, on public land, and following basic engineering standards intended for affordability rather than longevity, their replacement costs appear modest. Conventional asset-based disaster assessments, therefore, tend to classify irrigation as a 'low-cost' sector with limited fiscal relevance.

Yet this framing is profoundly misleading. Irrigation assets underpin disproportionately large shares of agricultural output, rural incomes, and climate resilience. Small disruptions to water delivery can trigger yield losses, food price spikes, rural income collapses, knock-on effects across supply chains, as well as downstream effects such as migration and displacement (Rau & Sridhar, 2025). The true consequences of irrigation failure are therefore not captured by the monetary value of a broken canal or damaged headworks, but by the cascading impacts on food systems, livelihoods, and national economic stability.

This low replacement cost but high systemic importance paradox of irrigation infrastructure is the core reason irrigation infrastructure has not received greater attention in national and global policy agendas. This must change in the future. Protecting irrigation systems is not simply an engineering necessity, but a national food security priority, a climate adaptation strategy, and a safeguard for social stability. The argument for investing in irrigation resilience becomes even stronger when one considers the combined pressures of climate change, demographic shifts, water scarcity, and the growing interdependence between rural and urban economies.

Therefore, safeguarding local and national irrigation systems against disaster risk goes beyond protecting canals and dams—it is about securing the food systems that sustain billions of people worldwide.

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