CDRI
Coalition for Disaster Resilient Infrastructure

Global Infrastructure
Resilience Working Paper

Technologies

Harnessing the full potential

GIR TECHNOLOGIES
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 "*Technologies: Harnessing the Full Potential*" examines how a broad spectrum of technologies can enhance infrastructure resilience, while identifying the opportunities, limitations, and enabling conditions for their adoption. 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 CDRI website, 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

AAL	Average Annual Loss
AI	Artificial Intelligence
BIM	Building Information Modelling
CDRI	Coalition for Disaster Resilient Infrastructure
DRR	Disaster Risk Reduction
FinTech	Financial Technology
GeoAI	Geospatial Artificial Intelligence
GIRI	Global Infrastructure Risk Model and Resilience Index
GIS	Geographic Information System
GPS	Global Positioning System
IADB	Inter-American Development Bank
ICT	Information And Communication Technology
IFI	International Financial Institution
IoT	Internet of Things
LEO	Low-Earth Orbit
LMIC	Low- and Middle-Income Countries
MEL	Monitoring, Evaluation, and Learning
ML	Machine Learning
NFC	Near-Field Communication
PPP	Public–Private Partnership
SCADA	Supervisory Control And Data Acquisition
SIDS	Small Island Developing States
UNDRR	United Nations Office for Disaster Risk Reduction
VR	Virtual Reality

Glossary

Artificial intelligence
The simulation of human intelligence in machines programmed to think, learn, and make decisions autonomously, improving performance over time.

Machine learning
A subset of AI that enables systems to learn from data and improve without being explicitly programmed, often used for predictive analytics and pattern recognition.

Internet of Things
A network of physical devices with sensors and connectivity that enables them to collect and exchange data.

Remote sensing
The acquisition of information about Earth's surface using satellites or aircraft to detect and monitor physical characteristics and environmental change.

Building information modelling
A digital representation of the physical and functional characteristics of an asset used in construction and infrastructure management to improve planning and efficiency.

Digital twins
A dynamic virtual model of a physical asset, process, or system that uses real-time data to simulate, monitor, and optimize performance throughout its life cycle.

Geographical Information System (GIS)
Computer-based tools that capture, store, analyse, and visualize spatial or geographic data for decision-making in planning, infrastructure, and environmental management.

Cloud computing
Delivery of computing services, such as servers, storage, databases, networking, and software, over the internet, or 'the cloud', to offer flexible resources and scalability.

Edge computing
A distributed computing framework where data processing occurs closer to the data source, reducing latency and bandwidth use, compared with cloud-only systems.

Big data
A distributed computing framework where data processing occurs closer to the data source, reducing latency and bandwidth use, compared with cloud-only systems.

Chatbots

AI-driven conversational agents designed to simulate human dialogue, providing automated responses or guidance via text or voice interfaces.

5G connectivity

The fifth generation of mobile network technology offering faster speeds, lower latency, and greater connectivity for large-scale device communication.

Virtual reality

An immersive computer-generated environment that allows users to interact with simulated real-world or imagined experiences in 3D space.

Blockchain

A distributed digital ledger technology that records transactions securely and transparently across multiple computers without a central authority.

3D printing

A manufacturing process that creates three-dimensional objects layer by layer from digital models, used for rapid prototyping and customized production.

Robotics

The design, construction, and operation of automated machines capable of performing complex tasks.

Web 3.0

The next generation of the web characterized by decentralized networks, semantic understanding, and enhanced user interaction and ownership of data.

Quantum computing

An advanced field of computing that uses quantum mechanical phenomena to process information exponentially faster than traditional computers for certain tasks.

Carbon wrapping

A method of strengthening concrete or other structural elements using carbon-fibre-reinforced polymer materials to enhance durability and load-bearing capacity.

Key Messages

1 A review of more than 35 new technologies and several global case studies shows that technology is poised to radically transform resilient infrastructure over the next decade.

2 Technologies such as resilient 3D-printed homes, low-earth orbit satellites, and artificial intelligence are no longer futuristic visions for disaster planning and response. They are already shaping disaster resilient infrastructure.

3 There are three areas with the greatest potential for technological transformation of resilience in infrastructure before, during, and after disasters: (i) enhancing the data value chain; (ii) improving connectivity, communication, and collaboration; and (iii) strengthening infrastructure assets and network performance.

4 Technology for resilience pays. Investments are generally a small portion of the overall cost of infrastructure assets and can significantly reduce the direct and indirect impacts of disasters. The cost of new technologies is a fraction of the cost of infrastructure service interruptions.

5 The benefits of new technologies for resilience can be short-lived if infrastructure agencies and asset operators fail to adapt. Infrastructure agencies need strong support from national governments, including robust standards and clear incentives. In addition, the staff and customers of infrastructure agencies need new skills to interpret the tools and outputs of technology effectively.

6 The private sector can be an ally in the technological transformation for resilience. However, private sector partners require clear guidance, expectations, and flexibility to innovate and fully realize the potential benefits of resilience.

7 Technology is evolving rapidly — its integration into resilience efforts should too. New infrastructure should be designed in a manner that can easily accommodate evolving technologies.

8 Building resilience in infrastructure does not require high-tech solutions. Simple, accessible solutions such as mobile apps for maintenance or communications with communities can be as transformative as AI or digital twin solutions.

1. Introduction

Technological innovation is transforming the way that infrastructure is designed, built, operated, and managed to better cope with the increase in disaster and climate risks. From digital platforms that provide real-time risk information to advanced materials that improve the durability of assets, technology is a critical enabler of capturing the resilience dividend. Yet, despite these possibilities, adoption remains fragmented, especially in low- and middle-income countries (LMIC), where capacity, financing, and institutional barriers can limit the scale and sustainability of technological solutions.

This background report has been prepared as part of the *Global infrastructure resilience: Capturing the resilience dividend* (GIR 2025) report, led by the Coalition for Disaster Resilient Infrastructure (CDRI). Building on the foundation of the GIR Report 2023 (CDRI, 2023b), this report transitions from exploring the concept of resilience dividend to examining how it can be effectively captured, with a specific focus on the role of technology in this process.

The purpose of this report is therefore twofold: first, to explore how technology can be used to build resilient infrastructure and, second, to provide governments, infrastructure agencies, and private-sector infrastructure operators with practical frameworks, pathways, and examples to help support the successful adoption of the technology required for resilient infrastructure. The report is organized around the three capacities needed for resilience across the disaster cycle: the capacity to absorb shocks, the capacity to respond to shocks, and the capacity to recover from shocks. It considers all elements of infrastructure assets, systems, and users to ensure that its recommendations are based on a holistic and comprehensive view of resilience.

Importantly, the report recognizes that resilience is not solely dependent on frontier innovation or advanced technologies. It examines how low-cost technologies may be more effective and sustainable in certain environments or for specific resilience goals. By focusing on both simple and advanced technologies, the report aims to provide stakeholders with the knowledge to make informed, context-sensitive choices that will lead to long-term success.

The ultimate objective is to support the report's mandate: to provide global leaders, policymakers, and practitioners with the evidence and practical tools needed to translate analysis into action, ensuring that infrastructure systems are not only safeguarded from shocks but also contribute to sustainable development gains.

The report starts with an introduction in Section 2, of a common framework to analyse the resilience of infrastructure. Section 3 reviews the opportunities that technology offers for resilient infrastructure and explores the ecosystem of stakeholders that can drive resilience through technology. Section 4 introduces an objectives-based framework for identifying the technologies that enhance resilience across the disaster cycle. It then explores emerging and future trends that are likely to shape the resilient infrastructure landscape in the coming years and addresses the core challenges and limitations that must be overcome for the effective adoption of technology, fostering infrastructure resilience. Section 5 shifts the focus from potential to implementation. It outlines seven foundational elements that create an environment conducive to successful technology adoption and provides a practical checklist and a four-stage process for assessing readiness and guiding improvement across institutions, infrastructure providers, and operators. Finally, Section 6 concludes the report with forward-looking recommendations and strategic priorities for advancing technology-enabled resilience in infrastructure planning and delivery.

2. Common Analytical Framework

The GIR 2025 report uses a common framework to analyse the resilience of infrastructure. This framework examines infrastructure not only as a collection of individual assets but also as networks of connected assets and the services they provide to individuals, communities, businesses, and the economy (CDRI, 2023a).

The resilience of these networks and services depends on their capacity to: i) resist and absorb the shocks caused by disasters impacts; ii) respond to the damages caused by those disasters and maintain basic levels of service continuity during crises; and iii) restore services as quickly as possible in a way that incorporates lessons learned from the disaster and reduces future loss and damage.
It is also essential to look at the resilience of infrastructure service users, which depends on their ability to: i) be better prepared and leverage the information provided by early warning system to reduce the shock of disasters; ii) find supplementary or alternative means to avail failed infrastructure services (e.g., back-up generators for electricity or alternative modes of transport); and iii) engage in the lesson learning process after disasters so that they are better prepared, together with the infrastructure agencies, for future disasters.

At these three levels (infrastructure assets, services, and users), resilience should be seen not only as the capacity to absorb the next disaster but also as the ability to respond to and recover from it. Building resilience in infrastructure assets and systems requires a comprehensive view of the resilience cycle. Figure 1 illustrates this cycle and the three capacities for an individual infrastructure asset.

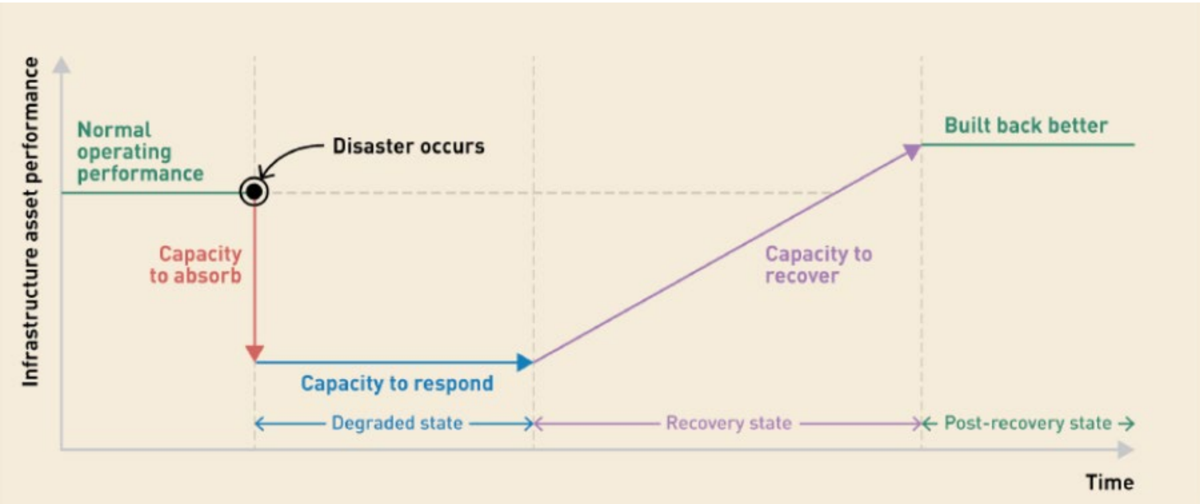

Figure 1: Three capacities for resilient infrastructure

Source: Adapted from CDRI (2023)

When a disaster occurs, the normal operating performance of an infrastructure asset may drop to a lower state (all the way to zero for a total failure). The magnitude of the drop depends on the capacity of that asset to absorb disaster shocks. Over a period of time, the asset is in a degraded state. During this time, emergency and clean-up actions are taken, and design and procurement of repair and reconstruction works are completed. These steps allow the infrastructure agency to start the recovery phase. The lessons learned from the disaster, including updated risk assessments that incorporate new hazard data and projected climate change impacts, are indispensable for designing the repair and reconstruction efforts of the infrastructure asset affected by the disaster. The recovery phase can then 'build back better' those assets. Many infrastructure agencies pay particular attention to the capacity to absorb by strengthening standards and regulations, implementing retrofit programmes for existing assets, and enhancing construction supervision for new, more resilient assets. They also expand maintenance and repair programmes to make assets stronger and ready for future disasters (like the cyclone season).

However, focusing only on the capacity to absorb is insufficient. The economic and livelihood impacts linked to interruptions of infrastructure services are directly related to the time it takes for the asset to be back to

full or enhanced operation. The longer it takes for the infrastructure asset manager to respond and recover, the larger the impact on households, businesses, and communities.
Figure 1 can also be used to understand the resilience cycle for infrastructure networks and services, where the capacity to recover services depends on the level of redundancy of the network, and 'building back better' requires a network analysis of vulnerabilities.

For users, the capacity of individuals, households, communities, and businesses to respond to infrastructure failures depends on the quality of two-way communications between infrastructure service providers and users, as well as the users' resilience in finding alternative means of service provision.
Building the resilience of infrastructure systems requires agencies and asset managers to strengthen not only the capacity to absorb disasters but also the ability to respond to shocks and recover quickly. Figure 2 shows the resilience-building process that strengthens the three capacities.

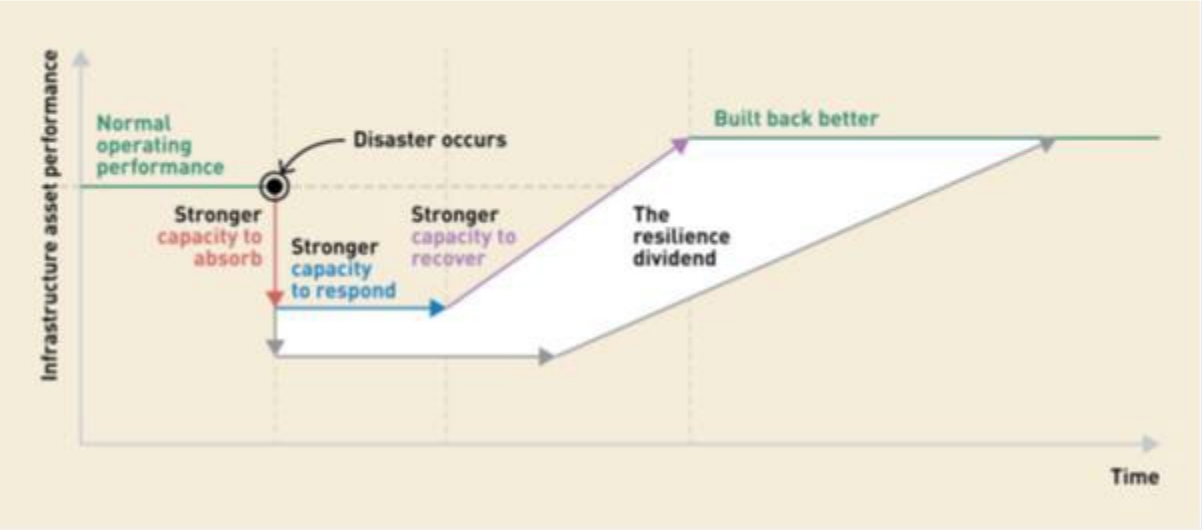

Figure 2: Strengthening the three capacities for resilient infrastructure and the resilience dividend

Source: Adapted from CDRI (2023)

An infrastructure agency or asset owner can implement several measures to strengthen the capacity to absorb (shorter red line on the left-hand side of the graph), such as developing enhanced maintenance, repair, and retrofit programmes or using systems that translate early warning notices sent by hydrometeorological services into preparatory actions to protect assets.

A stronger capacity to respond requires infrastructure agencies to be better prepared for disasters, and to have strong coordination plans with the national disaster risk management agency, emergency services, and other infrastructure agencies or utilities that provide linked services that can fail in a cascade after disasters. Some of these actions to strengthen the capacity to absorb include preparedness plans to remove debris from the asset; early procurement of stand-by repair services, including strategic location of repair materials; or use of new technologies for rapid assessment and evaluation of damages using drones.
Finally, infrastructure agencies or asset owners can strengthen their capacity to recover (represented by the purple line) by implementing post-disaster evaluation and learning activities; defining new tools (such as nature-based solutions or new technologies) to be incorporated in the repaired asset; and enhancing resilience standards in the repair and reconstruction efforts.

All the efforts in strengthening the three capacities will lead to less damage and degradation of performance, less time to respond, and more effective repair and reconstruction processes in case of a future disaster or similar magnitude. The strengthening of the three capacities will also lead to a faster restoration of services and a lesser impact on livelihoods and the economy. The white area in the graph visually represents the 'resilience dividend' of those efforts. It is defined as 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.

This framework is consistently applied across various chapters of this report, including surveys of businesses and resilience professionals, as well as analyses of technologies, finance, nature-based solutions, and institutions for resilient infrastructure.

3. The Technology for Resilient Infrastructure: Opportunity and Ecosystem

3.1. The Technology Opportunity

Infrastructure resilience—the ability of critical infrastructure, such as transportation, energy, water, and telecommunications, to anticipate, withstand, recover from, and adapt to disasters—is crucial for sustainable development, economic stability, and growth. However, globally, infrastructure remains highly vulnerable, especially in LMICs, where inadequacy in infrastructure resilience magnifies the devastating impacts of disasters.

The Global Infrastructure Risk Model and Resilience Index (GIRI) estimates an average annual loss (AAL) of $700 billion[1] for infrastructure and buildings (CDRI, 2023b). The scale of the risk and the devastation caused are enormous, and trends indicate that annual losses are increasing over time (EM-DAT, 2023). Thus, investing in disaster-resilient infrastructure would protect economies, reduce disaster recovery costs, and ensure the continuity of essential services crucial for sustaining livelihoods. This, in turn, would enable communities and economies to recover quickly, thereby preventing long-term economic decline in the affected regions.

The interconnectedness of infrastructure systems significantly increases their vulnerability and risk. Infrastructure seldom fails in isolation; rather, failures propagate and cascade across interconnected networks, intensifying social and economic disruption and driving longer-term impacts (Rehak & Hromada, 2018). For instance, Hurricane Maria's devastation in Puerto Rico in 2017 caused a prolonged collapse of the energy grid, severely affecting water supply and healthcare services (World Bank, 2019). More recently, the nationwide shutdown of the electricity network in Spain in April and May 2025 triggered ripple effects across various infrastructure services, including rail and road transportation, airports, telecommunications services, education and healthcare services, and water supply networks.

The global infrastructure investment deficit is projected to reach $15 trillion by 2040, and if resilience is not integrated into each infrastructure investment, risks will continue to grow (World Economic Forum, 2025). Globally, over 90 percent of disaster-related fatalities occur in LMIC (UNDRR, 2015), where the adoption of technology is limited (World Bank, 2023b) and infrastructure is less resilient. This failure to harness the power of technology in the planning, design, operation, maintenance, and disaster management of infrastructure leaves such countries more vulnerable to disaster risks, increasing exposure, exacerbating vulnerability, amplifying losses, and ultimately stunting economic growth. Incorporating technologies into infrastructure after construction is generally more costly than integrating them at the design stage. This reinforces the importance of embedding technology early in new infrastructure planning, while still recognizing the significant benefits that can be achieved by upgrading existing assets and systems.

Within this context, technology offers numerous transformative opportunities to enhance resilience across intricately interconnected infrastructure assets and networks throughout the infrastructure life cycle and the disaster cycle. Technologies such as remote sensing, artificial intelligence (AI), Internet of Things (IoT), and advanced materials can detect early signs of failure, enable rapid communication and decision-making, and provide alternative service delivery pathways. They can also help quantify risk and inform better investment planning, reducing long-term costs. Advanced computer modelling of complex systems can help identify infrastructural vulnerabilities. Monitoring systems using sensors and the IoT provide real-time insights into infrastructure performance, enabling predictive maintenance and reducing downtime. Technology used in the collection, analysis, and application of data can help inform decisions, enabling preemptive and responsive actions to be carried out in a coordinated way, thereby increasing resilience and reducing vulnerability to disasters. Technology can also enhance communication among key stakeholders, including infrastructure users, thereby increasing resilience. Thus, countries that integrate technology into infrastructure systems not only protect assets and lives but also enhance productivity, sustainability, and inclusiveness.

There are attractive financial benefits to technology-enabled resilient infrastructure, including lower life-cycle costs, improved service continuity, and lower insurance premiums. The World Bank's *Lifelines* report estimated that the net benefit on average of investing in more resilient infrastructure in LMICs would be $4.2 trillion, with a benefit of $4 for each $1 invested (World Bank, 2019). Some analysts suggest even higher benefit–cost ratios for certain disaster mitigation measures, with benefits of $6 or even $13 for every $1 invested (Multi-Hazard Mitigation Council, 2019). Deloitte (2025) estimates that AI could help avoid approximately $70 billion in annual losses in infrastructure by 2050. These savings in costs can be achieved through automated inspections and predictive maintenance, leading to increased operational efficiencies, reduced unplanned downtime, and extended asset lifespans, which would ensure that economic streams are protected. For example, an estimated £1 million was saved by using drones to inspect the Humber Bridge, United Kingdom, while simultaneously improving the safety and speed of inspections (Anvil Labs, 2023). Moreover, new technological approaches such as modular construction, 3D printing, and nature-based solutions integrated with digital design tools offer cost-efficient and adaptive alternatives. In developing countries, these innovations can leapfrog conventional development models, creating inclusive and locally tailored solutions (McKinsey & Company, 2019).

Technological innovation continues to progress, creating more opportunities to harness it for resilient infrastructure. Trends such as open data platforms promote transparency, collaboration, and informed decision-making throughout the disaster cycle. Digital advancements in generative AI, enhanced (super) computing capacities, and virtual reality (VR) can transform infrastructure management, scenario planning, and disaster response capabilities. Expanded connectivity, driven by widespread internet access and satellite constellations, such as SpaceX's Starlink, can significantly improve communication reliability during disasters, especially in scenarios where connectivity for disaster management, information sharing, and response coordination has been a major challenge previously. Technological advancements in hardware further contribute to resilience. For example, drone technology paired with advances in software capabilities can provide additional data at critical times. Improvements in battery technology, which have led to increased storage capacities and charging speeds, can keep infrastructure operational if electricity grids are impacted by a disaster. Innovative construction practices can also substantially enhance resilience by incorporating advances in building codes and practices, as well as through the use of innovative materials that would better survive disaster shocks and stresses. Emerging methods such as 3D printing and modular construction enable rapid, robust, cost-effective construction, with notable examples including homes constructed in Malawi and Kenya (World Economic Forum, 2021). Next-generation technological capabilities such as quantum computing, advanced AI with synthetic data generation, digital identities, and Web 3.0/metaverse environments can radically reshape resilience in the future. These technologies will continue to create opportunities to enhance infrastructure resilience throughout its life cycle.

Apart from the obvious effects, technology adoption offers many additional advantages. When infrastructure systems are made more resilient through technology, the benefits extend well beyond physical robustness to include safeguarding livelihoods, ensuring access to critical services such as health and education facilities during disasters. This enhanced, improved reliability then boosts economic productivity, reduces maintenance costs and further builds public trust in services. Resilient infrastructure also attracts private investment and supports long-term sustainability goals. As technology continues to evolve, many new opportunities for resilient infrastructure will emerge.

3.2. Definition and Scope of Technology for Resilient Infrastructure

Technology can be defined in many ways, but at its core, it refers to the practical application of knowledge to solve problems or achieve goals more effectively. Within technology, different groupings have specific definitions. Innovative or next-generation technologies push the boundaries of current capabilities by introducing new solutions or significantly improving existing processes. Disruptive technologies go further, transforming markets or creating new ones. Cross-industry technology involves borrowing or adapting tools, methods, or innovations from one sector and applying them to another. This may include open innovation practices, where technologies originally intended for one area are repurposed to address new challenges or improve processes in other areas. Such transfers can occur across industries, geographies, cultures, and market segments.

When working across diverse contexts, especially those with varying capacities and levels of technological maturity, it is important to distinguish between high-tech and low-tech solutions. High tech refers to advanced, often complex or digital innovations, whereas low tech includes simpler, more traditional or mechanical technologies. Both can play valuable roles in enhancing infrastructure resilience, depending on the local context, institutional capacity, and available resources.

This report considers the full spectrum of technologies that can contribute to the resilience of infrastructure systems, assets, and users. It encompasses both high- and low-tech approaches, such as well-established tools and pioneering innovations, as well as solutions originating within the infrastructure sector and those repurposed from others. The technologies discussed span both digital and analogue domains, offering improvements across the disaster and infrastructure cycles.

3.3. Key stakeholders in Technology for Resilient Infrastructure Ecosystem

Multiple actors are involved in overcoming challenges and achieving infrastructure resilience through technology. The ecosystem of stakeholders includes government, private sector, civil society, and international partners, each playing complementary roles in the planning, design, financing, deployment, operation, governance, and sustainability of resilient, technology-enabled infrastructure systems.

This report is primarily intended to support decision makers at the central government level and infrastructure providers, whether they are public-sector infrastructure ministries and agencies or private-sector infrastructure owners or operators. These entities play vital roles in national infrastructure planning, procurement, regulation, and long-term service delivery. They are responsible for ensuring infrastructure resilience with the mandates to adopt and integrate technology into infrastructure life cycles. This report provides these stakeholders with technical framing, examples, and policy-relevant insights to help them assess, adopt, scale up, and sustain appropriate technologies to improve resilience.

The success of resilient infrastructure efforts, however, depends on a much wider circle of actors. The key roles played by various stakeholders are described below and given in Figure 3.

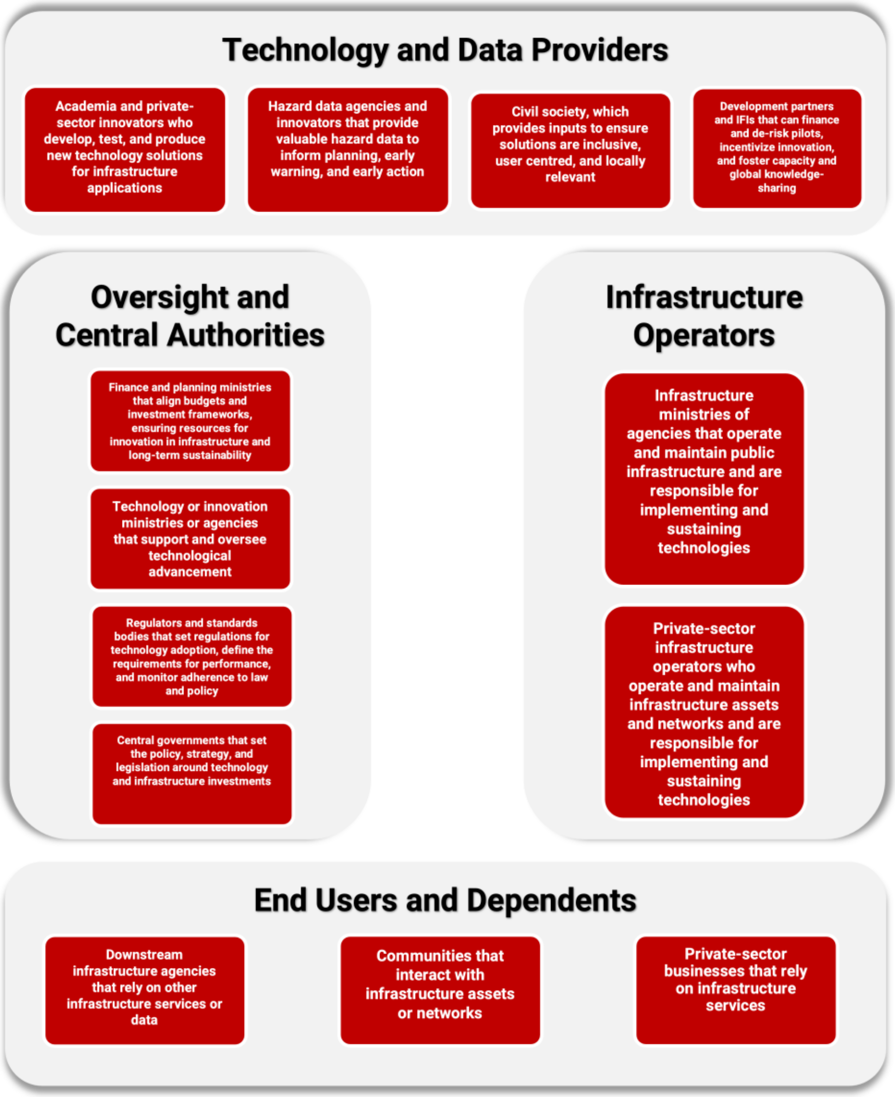

Figure 3: Key stakeholders to support technology for resilient infrastructure

Source: Authors' analysis

3.3.1. Technology and Data Providers

This group tests and pilots new technologies, developing user-centred, evidence-based, and globally informed solutions. It provides essential inputs, such as new tools, data, or local knowledge, which shape resilient infrastructure solutions. This group includes:

- **Academia and private-sector innovators:** From global tech firms to start-ups, construction companies, telecom operators, engineering firms, and software developers, these actors design, test, and deliver technology-based resilience solutions. They are a primary source of innovation and essential services for scaling technologies in infrastructure.

- **Hazard data agencies:** National disaster risk management agencies, meteorological offices, geological agencies, and climate service providers furnish critical hazard and climate data for planning, early warning, and early action. They are often consumers of technology themselves, and their data sets are indispensable for aligning infrastructure with national resilience, disaster risk reduction (DRR), and climate adaptation goals.

- **Civil society:** Citizens, communities, and civil society organizations are uniquely placed to provide insights into local needs and challenges. Their participation ensures that solutions are inclusive and equitable, and designed with the end user in mind, thereby enhancing sustainability and social acceptance.

- **Development partners and international financial institutions (IFIs):** IFIs and development partners provide financing, de-risking mechanisms, technical assistance, and global best practices. They can support pilots, incentivize innovation, and foster cross-country knowledge exchange and capacity building.

3.3.2. Oversight and Central Authorities

This group establishes the vision and strategies, creating a supportive environment for adopting technology in resilient infrastructure that also encourages innovation. They shape incentives and define requirements through policies, regulations, and financial frameworks. This group includes:

- **Finance and planning ministries:** Responsible for national investment frameworks and budget allocations, they ensure that resilience and technology are integrated into public investment systems. Their leadership helps secure funding for innovation, covering high upfront costs and the long-term sustainability of assets.

- **Central government, local governments, and municipalities:** Central governments set national policy, strategies, and legislation that guide infrastructure and technology investments. In some countries, local governments and municipalities may be responsible for some or all of these tasks. This group plays a vital role in ensuring that technology-enabled measures are appropriate to the context, community-oriented, and effectively implemented.

- **Technology or innovation ministries or agencies:** These institutions drive national digital strategies, regulate cybersecurity and data governance, and support national innovation ecosystems. They play a key role in promoting the adoption of emerging technologies in infrastructure and creating a conducive environment for them to thrive.

- **Regulators and standards bodies:** National and sectoral regulators establish the rules for technology adoption by setting performance standards, approving technologies, and ensuring compliance with laws and policies. Their oversight ensures that resilient design and operations are incorporated into infrastructure systems and that the use of technology is not unduly restricted.

3.3.3. Infrastructure Operators

This group is responsible for integrating technology in the planning, construction, operation, and maintenance of infrastructure. Implementers ensure that technological solutions are maintained, scaled, and continuously adapted to evolving risks and needs. This group includes:

- **Infrastructure ministries or agencies:** Public sector ministries and agencies are responsible for managing and operating infrastructure systems. They are the adopters of technology, responsible for integrating solutions into day-to-day operations, sustaining them over time, and ensuring they remain aligned with resilience priorities.

- **Private-sector infrastructure operators:** Private operators of utilities and infrastructure assets and networks are also technology adopters. By operating, maintaining, and upgrading infrastructure, they directly implement and test digital and resilience solutions, ensuring they are functional, scalable, and sustainable.

3.3.4. End Users and Dependents

This is the group that relies on infrastructure services, and their engagement, trust, and feedback are crucial to gauge whether the technology solutions delivered are meaningful and provide equitable benefits. This group includes:

- **Downstream infrastructure agencies:** Agencies that depend on other infrastructure services or shared data (e.g., water utilities relying on energy systems and transport agencies relying on communications networks) are both users and beneficiaries of resilient technologies.

- **Communities:** Citizens and local communities are the end users of infrastructure. Their perspectives are vital in ensuring that technology solutions address real needs, are inclusive, and remain sustainable over time. Involving communities in design and monitoring strengthens accountability and relevance.

- **Private-sector businesses:** Firms and industries that depend on infrastructure services (e.g., logistics companies relying on transport networks and manufacturers depending on energy supply) are key users of infrastructure. Their feedback helps align infrastructure technology with economic needs and market demands.

Stakeholders also share cross-cutting responsibilities. Some scan the horizon for emerging risks and innovations; others pilot technology and demonstrate proof of concept; many contribute to developing guidance and informing policy, building technical capacity, and monitoring, evaluation, and learning (MEL). For example, CDRI is developing a Data and Technology Strategy that addresses some of these cross-cutting issues. An overview of this work is presented in Box 1. Crucially, all stakeholders must observe, learn, and adapt based on how technologies perform during an actual disaster.

BOX 1. CDRI's Data and Technology Strategy

In response to the limitations and challenges, CDRI is launching a **Data and Technology Strategy** with the principal objective of equipping its member countries with the data, tools, and technological resources necessary to make risk-informed, strategic decisions on policies, regulations, and investments. This would strengthen the resilience of their existing and future infrastructure systems, as such data and technology could become strategic assets.

The expected outcomes of this strategic plan are:

- Member countries enhance and strengthen their capacity to generate, collect, analyse, utilize, and manage high-quality geospatial and infrastructure risk data, tools, and technologies.
- Member countries develop risk knowledge and analytical capacity to utilize and deploy models, tools, and technologies for assessing infrastructure risk and resilience.
- Member countries develop and adopt risk-informed policies and regulations.

This work is part of CDRI's ongoing efforts to support member countries in achieving their disaster-resilient infrastructure goals. This report focuses solely on technology and will form part of the basis for implementing this strategy as it relates to technology. While the challenges and opportunities around data specifically are not covered in detail in this report, the benefits of improved data are assumed herein. This report will discuss the technologies that can be implemented to support improved data environments, as well as those that require improved data environments to deliver their intended benefits to strengthen resilience.

Source: CDRI (2025)

Together, these stakeholders form an interdependent ecosystem. Coordination and collaboration across these groups, through clear strategies, data sharing, inclusive planning, and co-investment, are essential to achieve successful, effective, equitable, and sustainable deployment of technology for resilient infrastructure.

4. Mapping Technology for Resilient Infrastructure

As outlined in Section 2, there are opportunities to capture the resilience dividend through all stages of the disaster cycle by strengthening the capacity to (i) absorb, (ii) respond to, and (iii) recover from disasters. The various processes, challenges, and opportunities associated with each phase are unique and require different strategies and actions to increase capacity and resilience. Diverse technologies can be employed to support the various resilience-building objectives based on the needs of the infrastructure system. In this section,

- three core functions that technology can serve as it relates to increasing the resilience of infrastructure are presented;
- various technologies that enhance the capacity to absorb, respond to, or recover from the shocks caused by disasters are discussed; and
- the limitations and challenges of technology are explored.

4.1. Three Core Functions of Technology for Resilient Infrastructure

Available technologies that can support increased infrastructure resilience can be grouped in various ways. One common approach is descriptive, organizing technologies based on their nature or format, such as digital tools, analogue systems, advanced materials, construction techniques, robotics, computer modelling, or sensor networks. Another approach would be to group them on the basis of the phase of the infrastructure cycle in which they are used. For example, project preparation and design, procurement and construction, or operations and maintenance.

Alternatively, technologies can be categorized based on the resilience objectives they aim to serve. For example, some technologies enhance the data value chain, others strengthen communication and collaboration between stakeholders or infrastructure assets, while some improve the physical performance of infrastructure itself. With this grouping approach, technologies can belong to multiple categories. Drones, for instance, can improve data collection before disasters and provide real-time data during a disaster, as well as physically transfer items to areas that are remote or inaccessible. However, the reasons for the technology are clear: they help in achieving an objective.

Rather than focusing on the nature of technologies, this report adopts an objectives-based approach to help infrastructure decision makers identify the most pertinent technologies for building resilience. Technologies are grouped according to the core functions they support, allowing infrastructure providers to easily identify those relevant to addressing gaps and challenges and supporting improvements in these areas. The three core functions are:

- enhancing the data value chain;
- improving connectivity, communication, and collaboration; and
- strengthening the performance of physical infrastructure assets.

Together, these functions help create infrastructure capable of anticipating, withstanding, responding to, and recovering from shocks and stresses.

4.1.1. Enhancing the Data Value Chain

The first pathway focuses on the role of advanced technologies in improving the infrastructure data value chain—from data collection to decision support and learning. These technologies enable expanded, high-quality, and high-resolution data collection that can be real-time or near real-time if necessary, as well as automated and intelligent data processing, which is supported by improved computing capacity that speeds up processing. This subsequently leads to more accurate, evidence-based decision-making.

Resilience can only be developed if there is a clear understanding of the risks that the infrastructure faces. For this, it is crucial to obtain good-quality data, including better hazard, vulnerability, and/or exposure data. Improved data can also drive the performance of infrastructure systems by prioritising operations and maintenance activities through feedback on operations. Decision support systems, which consolidate multiple sources of data and automatically prioritize actions, can complete the data value chain. Similarly, during a disaster, data collection and generation of timely insights on disaster impacts will allow faster and more informed decisions to be made, driving prompt and appropriate action.

Data-related technologies significantly impact advances and transformative changes in infrastructure resilience and are expected to continue to do so in the future. Examples of technologies that can enhance the data value chain include the following:

- Sensor networks and IoT devices continuously monitor infrastructure assets. By detecting stress, overloads, or faults early, they reduce the likelihood of sudden failures, help prioritize preventive maintenance, and, thereby, improve resilience against shocks. For example, sensors on levees can provide early warnings of structural weakness before heavy rains cause potentially catastrophic failure.

- Remote sensing and drones enable detailed risk mapping, real-time surveillance, and rapid post-disaster damage assessment. They strengthen resilience by improving hazard monitoring, supporting exposure mapping, and accelerating emergency response. In flood-prone regions, drone imagery can quickly identify inundated areas and direct relief efforts.

- AI and machine learning (ML) analyse large volumes of hazard, vulnerability, and exposure data to forecast risks and create predictive models. They can support informed decision-making by bringing together vast amounts of data. For instance, AI-driven landslide models can anticipate slope failures, helping authorities issue timely warnings and reduce casualties. These systems enable more proactive and adaptive risk management.

- Building information modelling (BIM) and digital twins replicate infrastructure assets and networks in virtual environments. They strengthen resilience by simulating asset performance under hazard scenarios and optimizing retrofit and investment decisions. Digital twins of power grids, for example, can test how outages cascade and identify critical nodes to reinforce.

- Mobile data platforms and crowdsourced information bring community knowledge and real-time field data into resilience planning. Such inputs can improve vulnerability assessments by highlighting the disproportionate risks faced by informal housing, ageing infrastructure, or underserved populations. This ensures resilience strategies are more inclusive and tailored to specific contexts.

- Geographic information systems (GIS) and geospatial tools integrate hazard, exposure, and vulnerability data to provide spatial risk assessments for infrastructure systems and users. GIS can show how coastal roads intersect with storm surge zones or how schools in seismic zones overlap with poverty hotspots, directly informing resilience investment priorities.

- Cloud and edge computing enable faster, distributed analyses and improve the availability of critical data during crises. Cloud storage ensures that hazard and exposure data sets are backed up and remain accessible even if local infrastructure fails. Edge computing allows on-site processing, such as at a hospital or power plant, when connectivity is disrupted during disasters, maintaining the resilience of localized operations.

- Big data and advanced analytics identify trends and early warning signals from complex, multi-source data sets. One function of these systems could be to support anticipatory action; for instance, analysing traffic flows during evacuations to identify bottlenecks. Such insights allow governments to prioritize interventions and strengthen systemic resilience based on data and evidence.

By enhancing the entire data value chain, these technologies directly improve the collection of hazard, vulnerability, and exposure data. This translates into more accurate and opportune risk assessments, better-informed maintenance and investment planning, and more effective response and recovery efforts. Strengthening the data ecosystem is therefore vital for resilience because it ensures that infrastructure systems can anticipate, withstand, adapt to, and recover from shocks and stresses.

4.1.2. Improving Connectivity, Communication, and Collaboration

The second pathway highlights the importance of communication and coordination tools in enhancing infrastructure resilience, emphasizing inclusive communication with users. It includes technologies that improve the flow of information and finances between stakeholders, thereby transforming the way they interact, communicate, collaborate, and respond to crises. These technologies enable more effective digital collaboration and stakeholder coordination; quicker disbursement of financial aid to those in need during a disaster; tailored and inclusive crisis communication strategies to better target specific groups of users or infrastructure sectors; and improved early warning systems that facilitate timely action. Key technologies include:

- **Communication platforms**, **smartphones, social media,** and **chatbots**, which enable real-time, accessible communication with users and communities. AI can play a role in supporting these processes.
- **Satellite constellations and 5G connectivity**, which support reliable information exchange even in remote or disaster-affected areas.
- **VR** and **immersive simulation tools**, which offer solutions to improve the effectiveness of communication in disaster scenarios by providing a preview of the impacts of decisions made before and during crises.
- **Blockchain** systems, which support the transparent, rapid, and secure distribution of aid and cash assistance during the response and recovery phases.
- **Collaborative digital platforms**, which bring together actors for data sharing, asset management, operations and maintenance reporting, and joint infrastructure planning, project monitoring, and reconstruction tracking.

By improving the flow and reliability of information and coordination among actors, this pathway helps to anticipate disruptions and reduce the impact of disasters.

4.1.3. Strengthening Asset and Network Performance

The third pathway highlights the role of technologies that directly enhance the performance, durability, and robustness of physical infrastructure systems. These innovations improve how assets are designed, built, operated, maintained, and repaired, ensuring that services can continue to operate under stress and recover rapidly after disruption. By strengthening structural integrity, employing adaptive designs, and embedding redundancy, these technologies reduce the vulnerability of critical systems and help safeguard communities against a variety of hazards.

Some key technological applications are listed below:

- Advanced construction materials and modular construction practices improve the strength and adaptability of assets, minimizing damage during disasters and enabling quicker recovery. Examples include seismic retrofit technologies, such as carbon wrapping and steel reinforcement systems; fire-resistant cladding and insulation for wildfire-prone regions; and cool roof materials or reflective coatings that reduce heat stress in urban settings. Modular housing and infrastructure components can also be deployed rapidly after disasters to support recovery.

- Flood-resilient innovations are becoming increasingly important as climate risks intensify. These include amphibious housing designs that float during flood events, deployable flood barriers, and permeable pavements that absorb excess water, thus reducing flooding and enabling faster recovery. Smart pumping systems and automated floodgates, triggered by real-time monitoring, also strengthen urban flood protection.

- 3D printing technologies allow rapid reconstruction of housing or infrastructure components, reducing costs and downtime. In post-disaster contexts, 3D printing can accelerate shelter provision or rebuild damaged elements of bridges or culverts and even critical components that may become damaged and not be able to be replaced or procured rapidly in a post-disaster context.

- Robotics, including drones, can facilitate inspection, monitoring, and repair of critical infrastructure in hazardous environments. Robots can enter collapsed buildings or underwater systems to identify faults, while drones enable rapid structural assessments after earthquakes or hurricanes, reducing risks to human responders.

- Energy storage technology, such as batteries, ensures service continuity during outages or in remote areas. They not only strengthen power resilience through microgrids and renewable energy backup, but are also increasingly used in other infrastructure networks to maintain services despite fluctuations in the power grid. Solar-powered pumps can maintain water supply, and batteries can be used in health facilities to ensure uninterrupted service delivery during crises.

- Green and nature-based technologies offer sustainable, cost-effective protection while providing additional environmental and social benefits. Examples include mangroves that shield coastal infrastructure from storm surges, green roofs that reduce urban heat, and wetland restoration projects that absorb floodwaters and recharge aquifers.

Together, these technologies strengthen infrastructure resilience by reducing the likelihood of failure, enabling quicker recovery, and helping maintain essential services under stress. Enhancing asset and network performance is therefore central to protecting lives and livelihoods as climate and disaster risks intensify.

4.1.4. The Overall Framework of Technology for Resilient Infrastructure

The technologies characterized by the three pathways discussed earlier offer significant opportunities to enhance infrastructure resilience**.** Whether by improving the quality and use of data, strengthening communication and response coordination, or ensuring that physical assets can better withstand or respond to stressors, these approaches contribute collectively to a more robust, adaptive, and future-ready infrastructure system. The overall framework is given in Figure 4.

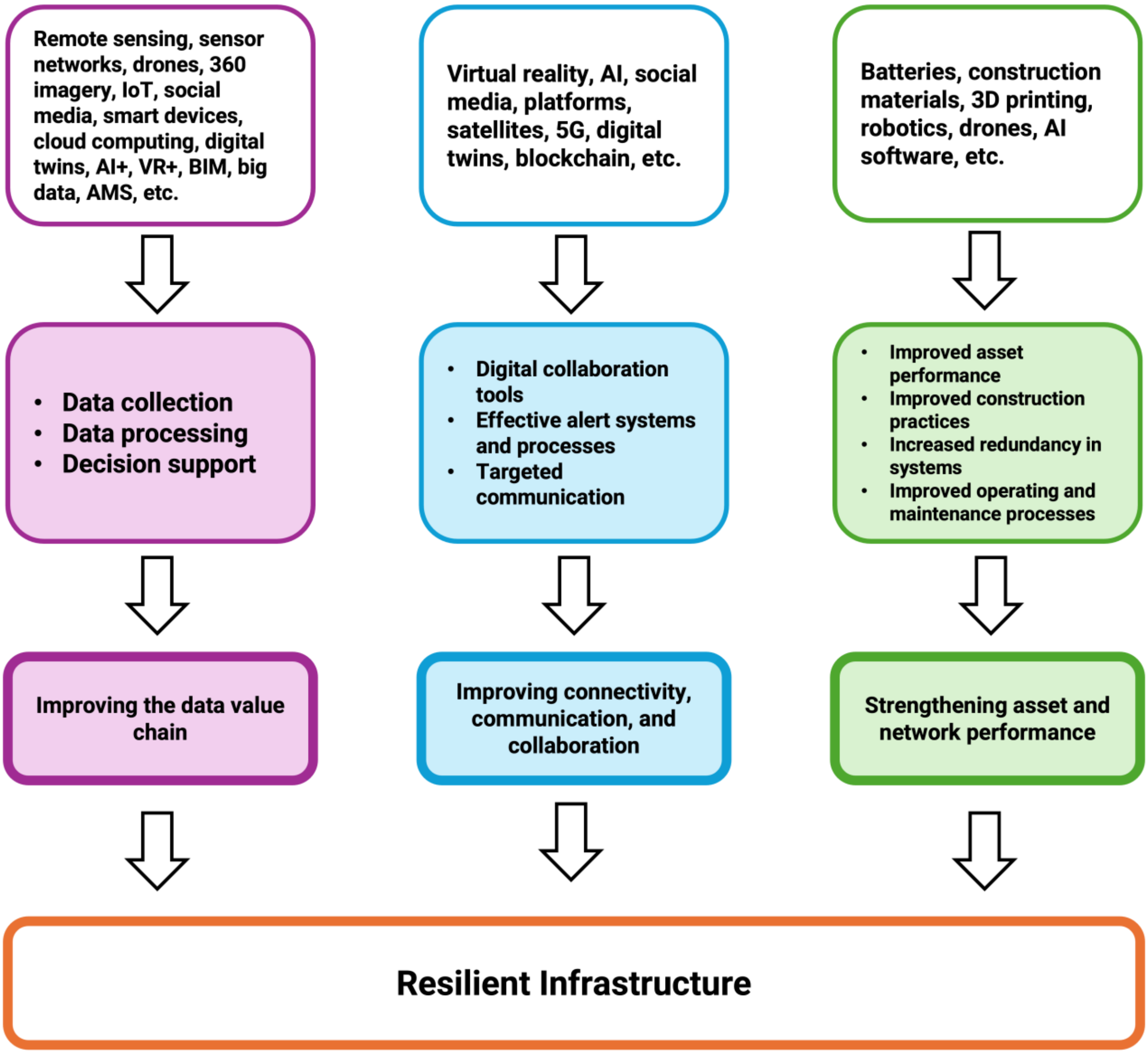

Figure 4: Framework for how technology builds resilience in infrastructure

Source: Authors' analysis

4.2. Technological Solutions for Resilience Objectives across the Disaster Cycle

The disaster resilience framework introduced in Section 2 identifies three core pathways to strengthen infrastructure systems and secure the resilience dividend: enhance the capacity to absorb shocks, respond effectively during crises, and recover quickly after disasters. Technology plays a critical role in each of these phases by improving the data value chain; enhancing connectivity, communication, and collaboration; and strengthening the performance of infrastructure assets and networks. These three technological functions underpin all resilience capacities and will be explored in detail in the upcoming sections.

Different technologies contribute to resilience in different ways across the absorb, respond, and recover phases. Their impacts may be direct or indirect, and they may benefit different infrastructure sectors and subsectors in different ways depending on how, when, and why they are deployed. It is especially important to consider how various infrastructure components can benefit and support resilience at different spatial scales, from individual assets (e.g., hospitals or schools) to infrastructure networks (e.g., road networks, multimodal transport systems, or power grids) and end users.

The infrastructure life cycle, which is critically important for infrastructure stakeholders, is also considered. This cycle and the disaster cycle can be represented in many ways, but for this report, the names and relationships between the two cycles provided in Figure 5 will be used.

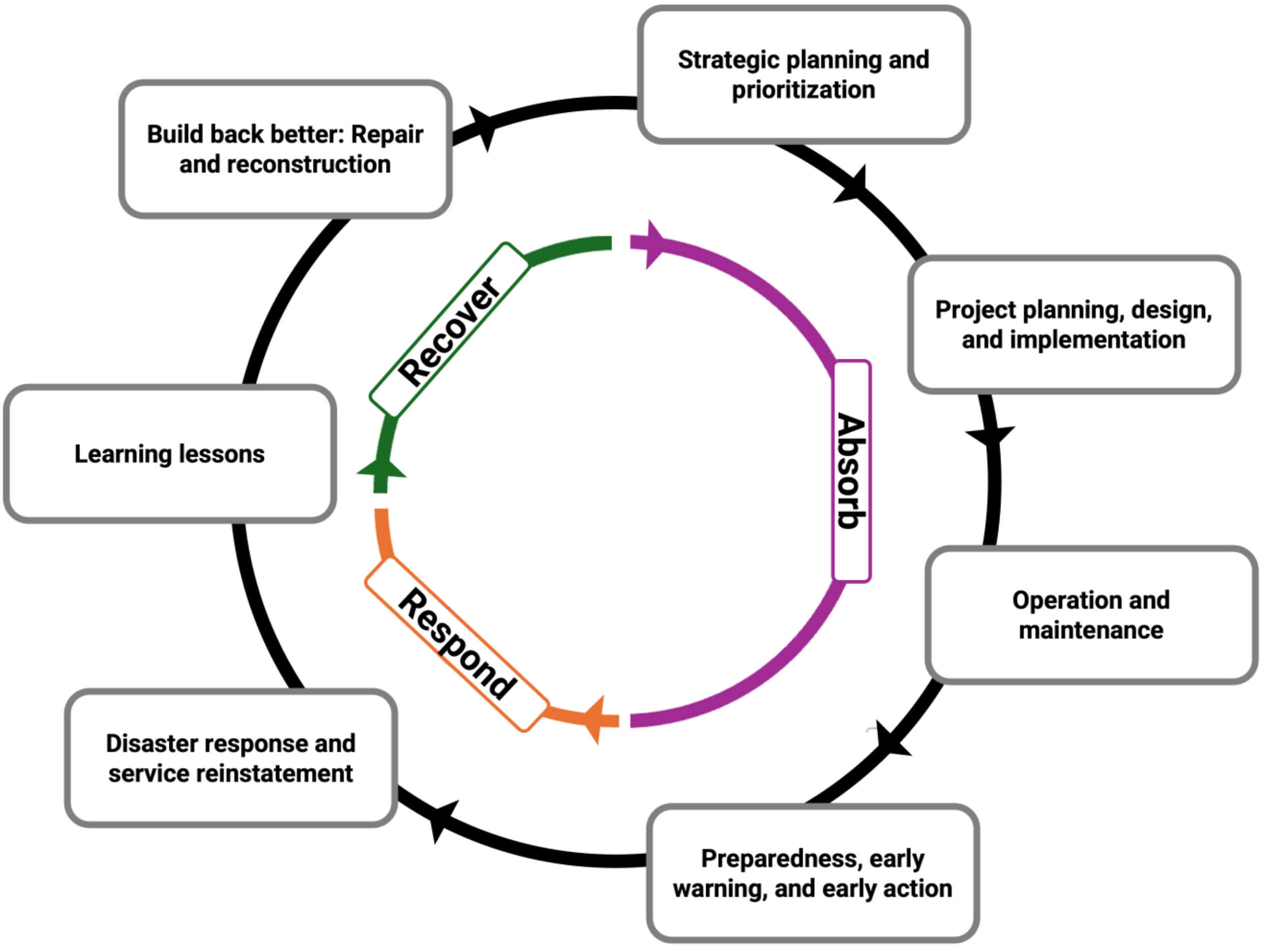

Figure 5: Connecting the disaster and infrastructure cycles

Source: Authors' analysis

The various applications of technology will be discussed in the following sections, supported by real-world case studies to illustrate how technologies are being used to build resilience in diverse contexts.

4.3. Building the Capacity to Absorb Shocks

Infrastructure systems must be able to withstand shocks without catastrophic failure and with minimal disruption to essential services. In countries with limited budgets and high hazard exposure, this absorptive capacity is vital for protecting lives, sustaining livelihoods, and preserving development gains. Such resilience cannot be achieved through any single investment but requires sustained efforts across the entire infrastructure life cycle, from planning and design to construction, management, and maintenance.

Technology plays a crucial role in strengthening the capacity of infrastructure to absorb disasters. As described above, it does so in three main ways: by improving the data value chain, enhancing connectivity and collaboration, and boosting the performance of assets and systems. These are not the preserve of high-income countries. Many increasingly affordable, scalable, and effective options are available in lower-resource contexts, where simple, well-adapted technologies can often deliver the greatest impact.

A sound understanding of risk is the foundation for resilience. Decision makers in ministries, agencies, and infrastructure utilities require timely, accurate, and location-specific risk information (see Case Study 1). Modern data systems and catastrophe models enable more precise assessments even in areas with historically limited local data, helping identify where to invest in new infrastructure and which assets to reinforce across complex interconnected networks (see Case Study 2). Yet, knowledge alone is insufficient because translating technical insights into actionable decisions remains challenging. Here, AI and related tools can translate complex metrics into intuitive guidance for prioritizing investments and reducing risk.

Case Study 1: Using AI to Build Exposure Data Sets: Google Open Buildings

Understanding exposure is critical for modelling and assessing disaster risk. However, accurate exposure data can be difficult to collect, especially in the Global South and at large scales. Google Open Buildings set out to solve this challenge for the buildings sector. They used AI models to detect the outlines of billions of buildings in the Global South. The resulting data sets cover both urban and rural settings and formal and informal housing and buildings. Data is provided on the size of the structure and the plan layout of structures. Temporal data show how settlements have changed over time, including building heights. The AI model has been trained to enable the detection of buildings using low-resolution satellite imagery to enable expansion to more areas. Research is ongoing on the use of AI to determine the construction materials of buildings from satellite and Google Street View imagery, which is important for accurate disaster risk assessments. However, challenges remain.

Source: Graham and Diack (2024); Sun et al. (2025)

Case Study 2: Modelling Interdependencies Between Different Infrastructure Networks and Assets in the United Kingdom

As climate change accelerates, the United Kingdom's (UK) infrastructure networks face growing threats from extreme weather events such as flooding, heatwaves, and high winds. These hazards do not impact infrastructure systems in isolation; rather, the interconnected nature of electricity, water, gas, and telecoms means that a failure in one area can trigger cascading disruptions across multiple sectors. To address these systemic risks, the Climate Resilience Decision Optimiser Plus (CReDO+) is being developed to help infrastructure operators anticipate and manage these interdependencies using cutting-edge digital twin technology.

CReDO+ builds on the original CReDO platform by simulating how infrastructure assets and systems perform under a range of future climate scenarios. By creating virtual replicas of physical infrastructure and integrating historical, real-time, and predictive data, the platform allows operators to visualize and stress-test asset performance and identify shared vulnerabilities. Importantly, CReDO+ incorporates economic and societal cost modelling to help infrastructure planners weigh investment decisions based on the broader consequences of failure, including service disruption, repair costs, and societal impacts.

A key innovation of CReDO+ is its ability to model interdependencies between infrastructure systems. For example, by integrating data from electricity and telecommunications networks, the platform can illustrate how a power outage triggered by a heatwave might disrupt digital communications and emergency response systems. This multi-sector perspective supports cross-sector planning and resilience through more coordinated resilience strategies.

Ultimately, CReDO+ is more than just a technical tool—it acts as a strategic enabler. By providing infrastructure planners with actionable insights into climate risks and system vulnerabilities, it supports smarter, more transparent, and more coordinated investment in long-term resilience. As the severity and frequency of climate hazards increase, tools such as CReDO+ will become vitally important for building infrastructure systems that are not only robust but also adaptable to an uncertain future.

Source: UK Power Networks (n.d.)

At the strategic level, technology supports long-term infrastructure planning. Improved data sets and digital investment platforms now integrate asset condition data, risk assessments, and socio-economic trends, helping ministries evaluate trade-offs and choose projects that deliver both development and resilience benefits. Such tools underpin national planning processes, climate-adaptation strategies, and disaster risk financing frameworks.

Effective governance is equally essential. Although many developing countries are reforming their construction governance systems, gaps in code enforcement continue to exist. Digital permitting platforms, automated design reviews, and BIM systems can improve compliance with updated codes and resilience standards. Meanwhile, low-tech solutions, such as online training, webinars, and technical help desks for builders and masons, directly strengthen capacity and resilience on the ground. These approaches enhance oversight without increasing administrative burdens for small community facilities and major transport corridors alike.

Technology also ensures that decision makers have real-time insight into infrastructure performance. Sensors, drones, robotics, digital twins, and IoT devices can feed live data dashboards that support proactive maintenance (see Case studies 3 and 4). These tools help bridge the gap between high-level analytics and operational action, benefitting both infrastructure managers and the communities they serve.

Case Study 3: Drones and Geospatial Artificial Intelligence (GeoAI) for Reducing Risk Through Prioritized and Intelligent Maintenance

Maintenance of infrastructure is vital for optimal everyday performance and disaster resilience. This can be a huge undertaking for large-scale infrastructure that spans vast areas, such as railways. Picterra, a Swiss technology start-up, in collaboration with Network Rail in the UK, has developed a GeoAI tool that analyses high-resolution drone imagery to detect minute changes in infrastructure and flag them for further human inspection and maintenance. The technology can detect even a small movement in a bolt fixing a rail to a railway sleeper and spot new hairline cracks that human walk-past inspections would not be able to detect, prioritizing issues for follow-up maintenance. The tool, thus, helps the infrastructure operator manage resilience and the capacity to absorb shocks.

This technology is available on a platform and can be trained to be used for any infrastructure typology or asset.

Source: Picterra (n.d.); In2Track3 (2024)

Case Study 4: Using Digital Twins to Monitor the New Bullard's Bar Dam, California

The Yuba Water Agency in California has developed a real-time digital twin for the New Bullard's Bar Dam, one of the tallest dams in the United States (US), to improve dam safety monitoring given seismic and flood risks. Built on Bentley's iTwin platform, the system integrates data from multiple sources, including drones and IoT sensors. The digital twin consolidates real-time data into a central platform, providing visual, intuitive insights into the dam's structural health and performance. The system's early warning capabilities enable proactive risk management through continuous monitoring.

This technology helps asset managers and engineers by improving data integration and accessibility, providing enhanced situational awareness for faster decision-making, and reducing inspection time and improving safety by allowing virtual walkthroughs.

Source: Bentley (2023)

In design and construction, digital tools can support more resilient outputs. BIM, 3D visualization, and VR simulations can model hazard scenarios, compare design options, and consolidate stakeholder feedback. Emerging methods such as 3D printing offer rapid, low-cost reconstruction opportunities in post-disaster settings (see Case Study 5), while advanced materials, such as self-healing concrete, are becoming increasingly accessible.

Operations and maintenance are crucial to sustaining resilience. Low-cost sensors and IoT devices can detect early signs of stress or failure, while GPS and traffic data enable smarter transport system management (see Case Study 6). AI-based predictive analytics further optimize maintenance scheduling, which is especially valuable when there are budget constraints and resources need to be allocated carefully.

Technology is equally important while retrofitting existing assets. ML, remote sensing, drones, and geospatial mapping can identify priority areas for intervention and are particularly useful in earthquake- and storm-prone regions. By directing resources towards the most vulnerable structures, governments can extend asset lifespan and reduce systemic risk on a prioritized basis.

Case Study 5: 3D Printing for Rapid, Low-cost Housing Reconstruction

Post-disaster housing recovery is often hindered by the limited availability of materials, skilled labour, and funding. To address this, Habitat for Humanity in the US has piloted the use of 3D printing technology to construct homes in under 30 hours at costs up to 20 percent lower than those with conventional methods. Similarly, 14Trees in Malawi has delivered fully printed homes for $10,000 in just 18 hours.

Large-scale robotic arms are used to extrude layers of specially formulated concrete, creating durable, disaster-resilient homes. The designs can be tailored to local hazard risks and adapted to community needs.

This technology could be employed by governments and recovery agencies working in resource-constrained settings. It enables fast, high-quality housing solutions at scale—ideal for rebuilding after major disasters—while also offering opportunities to localize production and establish new construction supply chains.

Source: World Economic Forum (2021); Habitat for Humanity (2021)

Case Study 6: FloodMapp for Real-time Flood and Traffic Management

In the US, an Australian company called FloodMapp has deployed a suite of tools called ForeCast, NowCast, and PostCast, which provide predictive as well as real-time flood data to emergency services and transport departments. The system integrates rainfall, river, and tidal data with predictive flood models and GIS to map potential inundation across urban areas.

ForeCast uses modelling to predict the impacts of floods on infrastructure. During major weather events, NowCast supports real-time traffic rerouting, helping emergency responders and the public avoid flooded roads. In the post-event phase, PostCast helps assess which infrastructure may have been affected and accordingly prioritizes inspections.

Dynamic tools such as FloodMapp, with the help of advanced modelling and GIS integration, support both response and early recovery activities, enabling faster decision-making, thus keeping roads safe and focusing inspections where they are most needed.

Source: FloodMapp (2024)

Preparedness is another key element of absorptive capacity. Infrastructure systems perform best when operational protocols, redundancies, and emergency resources are established before a crisis occurs. Technologies such as scenario modelling and VR simulations allow institutions to stress test and improve systems, identify weaknesses, and rehearse response plans (see Case Study 7). These exercises build familiarity and coordination across agencies, improving performance during real events.

Finally, technology underpins modern early warning systems. Satellite data, IoT sensor networks, and crowd-sourced platforms deliver faster, more accurate hazard detection, while ML enhances prediction and localization. In India, AI has been used to deliver tailored building-specific early warning messages, while in Ethiopia, simple coloured-pole systems along river banks allow communities to visually monitor rising water levels and issue alerts based on flood stages (see Case Study 8). These approaches give communities and service providers valuable lead time to take protective action, reducing losses and disruption.

Case Study 7: Virtual Reality for Preparedness in Trinidad and Tobago

To improve disaster preparedness in vulnerable communities, the Trinidad and Tobago Red Cross tested the use of VR technology to simulate disaster scenarios such as floods, hurricanes, and earthquakes. The immersive experience aimed to enhance preparedness, improve learning retention, and increase emotional engagement during disaster education campaigns to support the resilience of users. Participants experienced the realistic impacts of a disaster and practiced emergency responses in a controlled environment. VR can play a powerful role in strengthening individual and community preparedness, especially when combined with traditional outreach methods. Although this example is not directly related to infrastructure, it is possible to envision the potential use of VR technology in building infrastructure resilience. Indeed, these technologies have been applied to a potential dam failure scenario in the US.

Source: Solferino Academy (n.d.); Spero et al. (2021)

Case Study 8: Early Warning Communication Innovations

A simple but effective early warning system used at the community level involves placing colour-coded poles along riverbanks to indicate flood risk. As the water rises, communities can visually track warning levels and automatically initiate suitable preventive actions.

At the other end of the complexity scale, in India, SEEDS has used an AI-powered system that tailors cyclone warnings to individual households, using data on dwelling type, location, and hazard exposure. This approach was deployed ahead of Cyclone Yaas in 2021.

Together these examples highlight that both analogue and digital solutions have value, but must be context-sensitive, depending on capacity and need.

Source: Ajmal (2021); Gramener (n.d.); Practical Action Publishing (2010)

Collectively, these innovations strengthen the absorptive capacity in four key ways:

- New infrastructure is built to higher standards with smarter designs.
- Existing assets are upgraded through retrofitting and improved maintenance.
- Preparedness is enhanced through planning, training, and simulation.
- Early warning systems provide timely, actionable alerts for risk reduction.

In sum, technology offers practical and scalable pathways—some of which are increasingly affordable—for governments to strengthen the resilience of their infrastructure systems. By integrating these tools into policy and practice, ministries and infrastructure operators can reduce risks, protect public investments, and deliver more reliable services to citizens. This discussion is summarized in Figure 6.

The next section explores other technologies that can further strengthen the capacity of infrastructure systems to respond effectively during disasters.

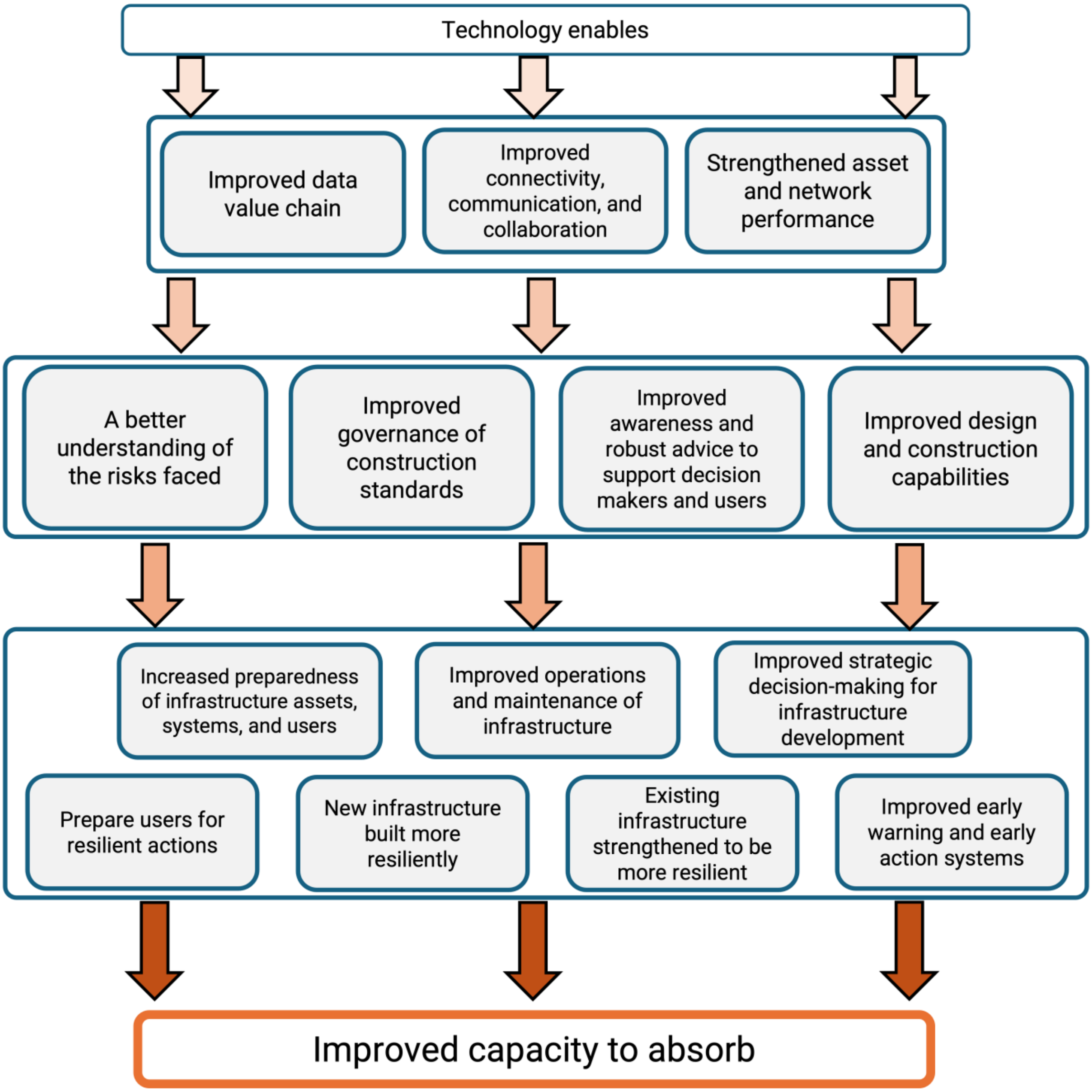

Figure 6: The pathways to resilience for technology in the capacity-to-absorb phase

Source: Authors' analysis

4.4. Strengthening the Capacity to Respond

When disaster strikes, infrastructure systems become the primary focus of response efforts. Roads must be cleared for rescue teams, power must be restored to hospitals and shelters, and water, sanitation, and communication networks must be brought back online to sustain essential services. The speed and reliability with which these systems are reinstated determine the scale of disruption and the effectiveness of emergency operations. This is the essence of the response phase: the urgent restoration of infrastructure to save lives, limit losses, and stabilize critical functions.

Effective response relies on a set of core enablers, all of which can be strengthened by technology. Governments, infrastructure ministries, and private operators face immense pressure to act swiftly and decisively. For this, they rely on timely and accurate information, coordination across agencies and authorities, rapid and flexible systems for resource deployment, and pre-established policies, tools, and protocols for emergency repair and temporary service delivery. Digital coordination platforms, remote-sensing tools, mobile communication systems, and modular engineering solutions enhance response speed and precision as well as the safety of rebuilt infrastructure.

A clear understanding of impacts and access to timely information are the foundation of any effective response. Technologies that strengthen the infrastructure data value chain—such as drones, satellite imagery, mobile assessments, and social media analytics—enable responders to assess damage in real time (see Case Study 9). Drones can quickly capture imagery of damaged infrastructure (see Case Study 10), while satellite services such as the Copernicus Emergency Management Service (n.d.) provide rapid assessments of affected buildings and networks. These tools support both asset-level evaluations (e.g., a collapsed bridge or hospital) and system-wide assessments of transport, energy, and communication corridors. The World Bank's GRADE methodology (World Bank, 2018) complements these tools by generating rapid economic damage estimates across key sectors (residential, non-residential, infrastructure, and agriculture) to inform early recovery planning and prioritization.

Case Study 9: FireSat Satellites for Real-time Wildfire Detection and Response

Managing wildfires in real time requires continuous, reliable data on fire location, intensity, and movement. In the US, the proposed FireSat satellite constellation, a joint effort by NASA's Jet Propulsion Laboratory and the Department of Homeland Security, aims to provide real-time thermal imaging of wildfires across the globe.

Once deployed, FireSat's sensors will detect heat signatures from space and relay this information to fire management agencies within minutes. The system is designed to support integration with national fire management platforms, enabling quicker response decisions, evacuation orders that prioritize safety, and better use of firefighting resources.

This space-based capability enhances traditional land- and drone-based fire detection, especially in remote or inaccessible areas. For infrastructure managers, the system will also offer early alerts about fires approaching critical assets, such as transmission lines, highways, or water reservoirs, enabling protective measures to be taken in advance.

Source: FireSat (n.d.)

Case Study 10: Drones for Rapid Post-disaster Damage Surveys

After major disasters, accessing and surveying affected areas is often slow and dangerous. It was recently reported that 80 percent of prefectures and 20 major cities have used drones to assess the post-disaster situation through aerial photography. The UK's Earthquake Engineering Field Investigation Team (EEFIT) first used drones to map damage to buildings after the 2016 Muisne earthquake in Ecuador.

These drones capture high-resolution images that can be stitched into maps and 3D models, allowing engineers to assess structural damage, identify blocked roads, and prioritize response. The data is integrated into GIS systems and made accessible to emergency services.

This approach enables much faster decision-making and is also safer for responders, especially in remote or unstable areas. It also helps governments allocate resources, coordinate repairs, and document needs for funding or insurance. Training local infrastructure stakeholders to operate drones increases infrastructure preparedness and response capacity.

Source: EEFIT (2018); The Institution of Structural Engineers (2017); Gramener (n.d.)

Real-time coordination and communication are equally critical in disaster response. Identifying what has failed is only part of the challenge; effective collaboration among authorities, across ministries, utilities, emergency services, and local governments is also necessary. Connectivity solutions such as 5G networks and low-earth-orbit (LEO) constellations (e.g., Starlink) ensure that communication is not affected even when terrestrial systems fail (see Case Study 11). Cloud-based coordination platforms, emergency operations dashboards, and backup power systems from batteries or local generators also ensure that communication is maintained, enabling multi-agency collaboration. These technologies allow authorities to monitor infrastructure functionality, manage reduced-capacity networks, prioritize emergency teams and repair crews, and provide real-time guidance to users. During the 2024 Rio Grande do Sul floods, for example, a digital dashboard integrating live impact data improved coordination across multiple infrastructure sectors (see Case Study 12).

Case Study 11: Starlink to Restore Connectivity in Disaster Zones

One of the most immediate challenges when disaster strikes is the breakdown of communications infrastructure, which hampers emergency coordination and disrupts access to critical services. LEO satellite systems, such as Starlink, are proving critical for maintaining connectivity in crisis-affected areas.

During the 2022 Tonga volcanic eruption, Starlink terminals were rapidly deployed to re-establish internet access after underwater fibre cables were damaged.

The terminals are lightweight, require minimal set-up and can be deployed in remote or disaster-affected areas independently of terrestrial infrastructure.

These systems provide fast, reliable internet to field teams, allowing video-based damage assessments, real-time mapping, and cloud-based data sharing. They also support communication with communities and remote management of assets such as power grids and water systems.

Source: Needham (2022)

Case Study 12: Disaster Impact Dashboards in Brazil

In response to the severe flooding that struck the state of Rio Grande do Sul in 2024, Brazil's Civil Defence rapidly developed and launched a publicly accessible online dashboard to track and communicate disaster impacts. The platform became operational within days of the disaster and served as a vital information hub for both the public and decision makers during the emergency response phase.

The dashboard provided real-time data on various critical indicators, including road closures, the operational status of healthcare facilities, statistics on shelters and displaced persons, the conditions of dams, and water levels in rivers and lakes. By aggregating and visualizing this data, the system offered a clear picture of the unfolding situation and enabled timely, informed decision-making.

This technological intervention played a key role in enhancing situational awareness and operational coordination. It served as a central communication tool for the government and emergency services, while also fostering public engagement and trust through transparent, accessible information. Moreover, the platform supported fundraising and relief efforts by clearly conveying the scale and severity of the crisis.

Source: Governo do Estado do Rio Grande do Sul (2024)

Rapid mobilization of finance, materials, and technical expertise is crucial in the response phase. Technology accelerates the restoration of services through innovations in logistics and engineering. Mobile power units, modular bridges, prefabricated clinics, and portable water-treatment systems can be pre-positioned and deployed rapidly. Diagnostic tools—such as structural-health sensors, ground-penetrating radar, and mobile testing labs—help engineers make quick, evidence-based decisions about whether assets are safe or repairable or must be replaced. Virtual assessments using drone imagery and 3D visualization further reduce the need for on-site inspections, minimizing delays and improving safety. Financial-technology (FinTech) platforms also facilitate transparent and traceable disbursement of emergency repair funds (see Case Study 13).

Responsiveness can also be embedded directly into infrastructure design. Smart grids can automatically isolate damaged sections of the power network to prevent cascading failures, while supervisory control and data acquisition (SCADA) systems in water utilities can reroute flows or shut down pumps to avoid contamination. Pre-positioned drones can be programmed to conduct post-event assessments or carry out rapid recalibration of airport equipment. These features require upfront investment, but they become invaluable in the event of a disaster.

Communities themselves play a key role in an effective response. Infrastructure operators can deploy mobile applications, SMS systems, and public information platforms to collect crowd-sourced data on outages and share updates about alternative services. In areas with limited digital connectivity, community radio and physical signage are the vital communication channels. Chatbots have proven effective in public health emergencies and can also be adapted for disaster contexts to provide localized, automated support to citizens (see Case Study 14).

Case Study 13: Blockchain for Transparent and Inclusive Recovery, Vanuatu

Following the destruction caused by tropical cyclones, the Government of Vanuatu, in partnership with the World Food Programme and the Connecting Business Initiative, piloted a blockchain-based digital cash transfer system to support housing reconstruction. As communities are widely dispersed across remote islands in this country, the challenge of delivering timely and transparent financial assistance is particularly acute.

To overcome these constraints, the programme used blockchain technology to register and track cash transfers to disaster-affected households. Each recipient was assigned a secure digital identity, and all transactions were recorded on a blockchain ledger, ensuring a tamper-proof and transparent distribution process. The system was designed to function offline using mobile phones and near-field communication (NFC) cards, making it operational even in areas with unreliable or no internet connectivity.

The transparency of the blockchain platform reduced opportunities for fraud and misallocation, while real-time transaction visibility fostered trust amongst recipients regarding the authorities' use of funds. Importantly, the system also enhanced inclusivity and local agency by allowing recipients to select their own recovery priorities: purchasing construction supplies, food, or healthcare. The system empowered recipients to choose how to use reconstruction funds, making recovery more inclusive and locally driven. This laid the groundwork for more accountable, people-centred disaster recovery models.

Source: Reach Alliance (2022–2023)

Case Study 14: Chatbots for Real-time Crisis Communication

During the COVID-19 pandemic and subsequent emergencies, organizations such as the World Health Organization (WHO) and DataKind developed AI-powered chatbots to enhance public communication and combat misinformation during crises.

Designed to operate in multiple languages and use minimal bandwidth, the chatbots provided guidance on access to healthcare infrastructure, amongst other things. This improved the capacity of infrastructure users to respond effectively to the crisis.

Chatbots are especially useful in crisis situations due to their scalability and automation. They require limited human input once deployed, making them ideal for situations where human resources are stretched. Most importantly, they serve as a means to counter misinformation by consistently relaying accurate messages from trusted authorities. This builds public trust and supports more effective response coordination in fast-moving emergency environments.

Source: WHO (2022)

Technology enables rapid and sound decision-making. AI-driven decision support systems can process large volumes of data to prioritize repairs and restoration. By automating analyses that would otherwise take days, these tools enable faster, evidence-based, transparent decision-making in critical scenarios.

The technologies discussed above improve response capacity by strengthening situational awareness, coordination, resource mobilization, embedded responsiveness, and user interaction. They enable governments and operators to restore infrastructure services more quickly, target resources more effectively, and protect both workers and users. These benefits extend across assets (such as schools or substations), systems (such as transport or power networks), and users (the communities who rely on them). Figure 7 illustrates how technology enhances resilience pathways during the response phase.

For countries facing high disaster risk, investing in these enabling technologies represents a strategic shift from reactive crisis management to proactive, coordinated response. Many of these tools are modular, scalable, and increasingly affordable, allowing ministries to modernize response systems at reasonable costs. The next section explores how these same technologies can sustain momentum through the recovery phase, helping countries rebuild stronger and more resilient infrastructure systems.

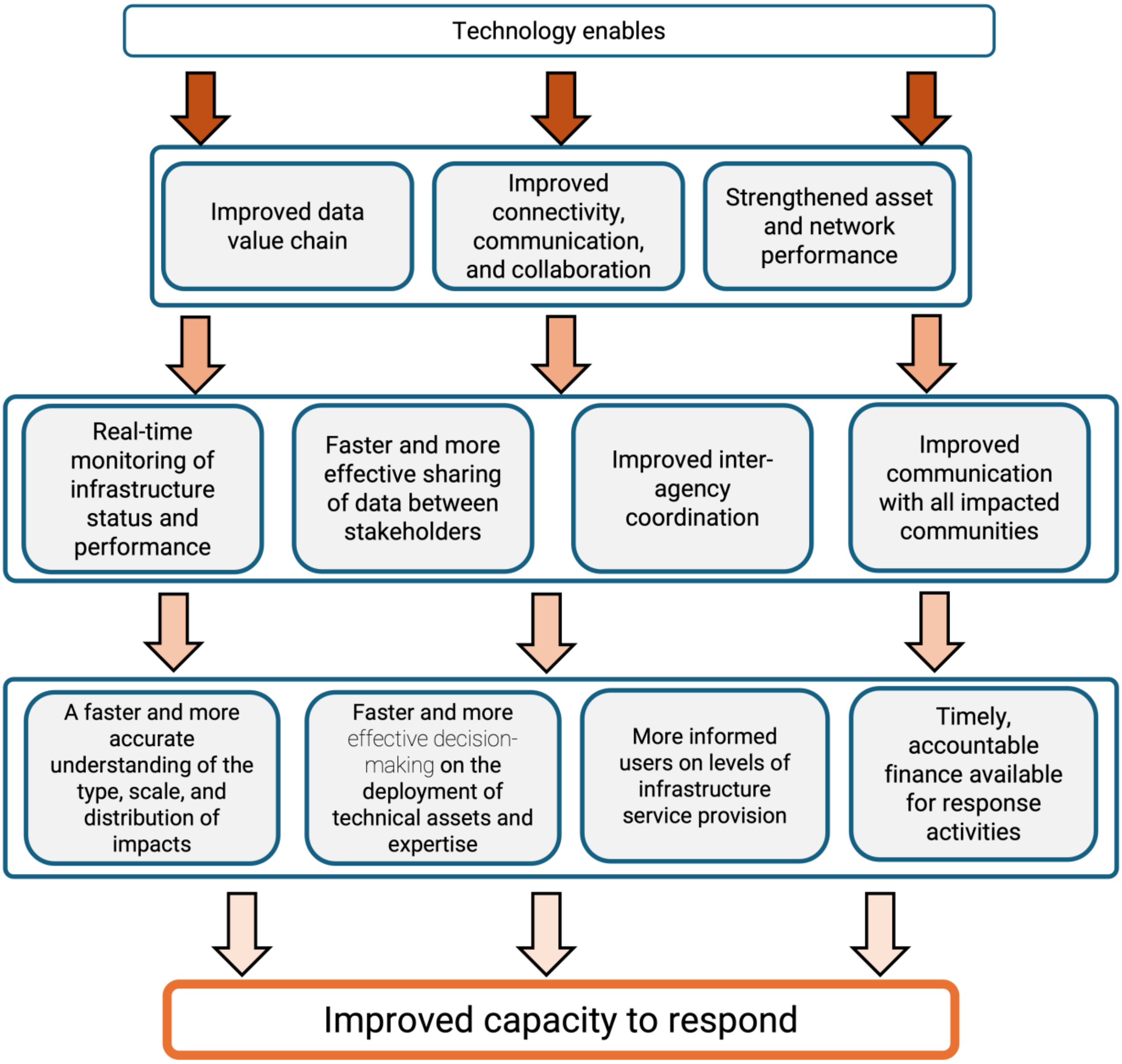

Figure 7: The pathways to resilience for technology in the capacity-to-respond phase

Source: Authors' analysis

4.5. Strengthening the Capacity to Recover

Recovery is more than reconstruction—it is an opportunity to rebuild in a more resilient manner. In the three to six months following a major disaster, governments transition from emergency response to long-term reconstruction, making decisions that have enduring consequences. The capacity to recover depends not just on how quickly services are restored, but also on the quality, performance, inclusivity, and resilience of the systems that are rebuilt. Recovery also encompasses the many smaller or recurrent events that may not make global headlines but have the potential to cause substantial cumulative losses. Technologies that streamline assessments, accelerate repair, and lower transaction costs can make these recovery processes faster, more affordable, and less disruptive. Mobile reporting applications, rapid drone surveys, and digital procurement tools, for example, can help shorten repair times for damaged roads or water systems, reducing service interruptions and economic losses.

Infrastructure ministries play a central role in the recovery process. They are responsible for assessing damage, prioritizing investments, coordinating reconstruction plans, securing financing, enforcing standards, and delivering systems that serve populations more reliably than before. Private operators bear comparable responsibilities for privately owned assets. However, the challenges are significant: damaged networks, incomplete asset data, fiscal constraints, multiple stakeholders, and the expectation to 'build back better'. In this scenario, technology becomes a critical enabler, enhancing the speed, precision, coordination, and accountability of recovery efforts across assets, systems, and users.

Technology supports recovery through the same three foundational functions that underpin absorptive capacity: improving the data value chain, enhancing connectivity and collaboration, and optimizing asset and network performance (Figure 8). Together, these functions facilitate better monitoring, governance, and cooperation, ensuring that reconstruction is resilient, inclusive, and efficient. Naturally, there should be overlap between the absorb and recovery phases, as the same systems and data platforms that help withstand shocks also guide recovery decisions.

A key enabler of recovery is the ability to monitor infrastructure and model performance as rebuilding progresses. Whereas emergency response focuses on identifying immediate failures, in the recovery phase, it is important to analyse why systems failed, what temporary measures succeeded, and how designs can be improved. Using pre- and post-disaster data, advanced modelling and analytics can inform reconstruction options and simulate long-term performance under different hazard scenarios. Real-time monitoring ensures that progress stays aligned with resilience objectives and that reconstruction avoids past vulnerabilities.

While infrastructure is being rebuilt, technology ensures that recovery adheres to safety and resilience standards. Up-to-date codes, standards, and digital design tools such as BIM allow reconstruction teams to integrate resilience measures into all repair and rebuilding work. When linked to national codes and standards or compliance checklists, BIM platforms provide automated quality assurance throughout the reconstruction process. Virtual training tools, including mobile apps, online courses, and recorded demonstrations, help strengthen capacity among engineers and contractors in contexts where technical expertise is limited (see Case Study 15).

Case Study 15: Mobile Monitoring for Safer Reconstruction in Nepal

Following the devastating 2015 Gorkha earthquake, Nepal faced the monumental task of rebuilding over 800,000 homes across some of the world's most remote and mountainous terrain. With limited numbers of trained engineers and dispersed rural settlements, maintaining quality, compliance, and safety in reconstruction presented a significant logistical and institutional challenge.

To address this, the United Nations Office for Project Services, in partnership with the Government of Nepal and several NGOs, deployed FieldSight—a mobile platform that enabled remote monitoring and technical supervision. FieldSight enabled engineers, project managers, and local builders to conduct site-level data collection, perform quality assurance inspections, and verify compliance with Nepal's updated earthquake-resilient building codes directly using a smartphone or tablet.

The platform offered a suite of digital tools, including GPS-tagged checklists, photo and video documentation, customized inspection templates, and real-time dashboards for centralized data analysis. It facilitated two-way feedback between national engineering teams and local construction sites, reducing the need for frequent on-site visits while still ensuring rigorous oversight.

By mid-2018, FieldSight had been used to monitor over 50,000 reconstruction sites across Nepal, supporting both government-led and NGO-supported efforts. This case highlights how mobile technology can enhance transparency, consistency, and safety in post-disaster recovery—particularly in resource-constrained and hard-to-reach areas—by bridging the gap between central oversight and local implementation.

Source: Kay (2020)

Because recovery involves multiple stakeholders, improved data sharing and inter-agency coordination are equally important. Duplication, delay, and misalignment with community priorities are common when there is a lack of coordination. Shared digital platforms can consolidate infrastructure assessments, project pipelines, and financial-flow summaries to improve transparency and decision-making. Financial management and e-procurement systems ensure that recovery funding is allocated promptly, responsibly, and efficiently. In high-risk or multi-agency contexts, blockchain-based platforms can further enhance transparency in reconstruction spending and reduce fraud, which is especially important when funds flow through several intermediaries.

Engaging communities is essential for successful recovery. Technologies such as SMS systems, mobile reporting apps, participatory mapping, 3D visualizations, and VR environments enable decision makers to collect feedback on infrastructure condition, service access, and rebuilding priorities directly from affected populations. In areas with limited connectivity, community radio and other offline methods remain vital. These engagement tools foster trust, enhance the inclusiveness of investments, and help ensure that rebuilt systems align with the real needs and preferences of users, building both resilience and social legitimacy.

Collectively, these technologies enhance the capacity of infrastructure to recover, contributing to greater overall resilience. The benefits are seen across assets, with repaired facilities being safer and better maintained; across systems, with restored and strengthened interconnected networks; and across users, with access to services being restored and communities being involved in decision-making. Together, they deliver three essential outcomes for resilient recovery.

First, technology facilitates faster and more effective decision-making during repair and reconstruction. Decision makers can identify which assets and systems to rebuild first, where resources can be allocated, and which interventions will restore critical functions most efficiently. AI-driven prioritization tools combine damage data, risk information, and community feedback to guide medium- and long-term recovery plans.

Second, technology embeds build-back-better principles into reconstruction. By integrating risk modelling, digital design tools, and code-compliance systems into planning and procurement, governments can prevent the replication of vulnerabilities in the rebuilt infrastructure and ensure that the new structures perform better under future stress.

Third, technology enhances transparency and targeting in the financial aspects of recovery. Digital financial management platforms enable real-time tracking of disbursements, improving accountability and ensuring that funds are used efficiently and equitably. Better information flow also helps conserve limited fiscal resources by avoiding duplication and ensuring that reconstruction aligns with resilience priorities.

For infrastructure ministries and operators in developing countries, investing in technology-enabled recovery systems should be a strategic priority. Many of these technologies are adaptable to different contexts and are increasingly cost effective. With the right institutional support, capacity building, and partnerships, they can transform recovery from a reactive process into a pathway for long-term resilience, one that not only restores what was lost but also lays the foundation for something safer, stronger, and more sustainable.

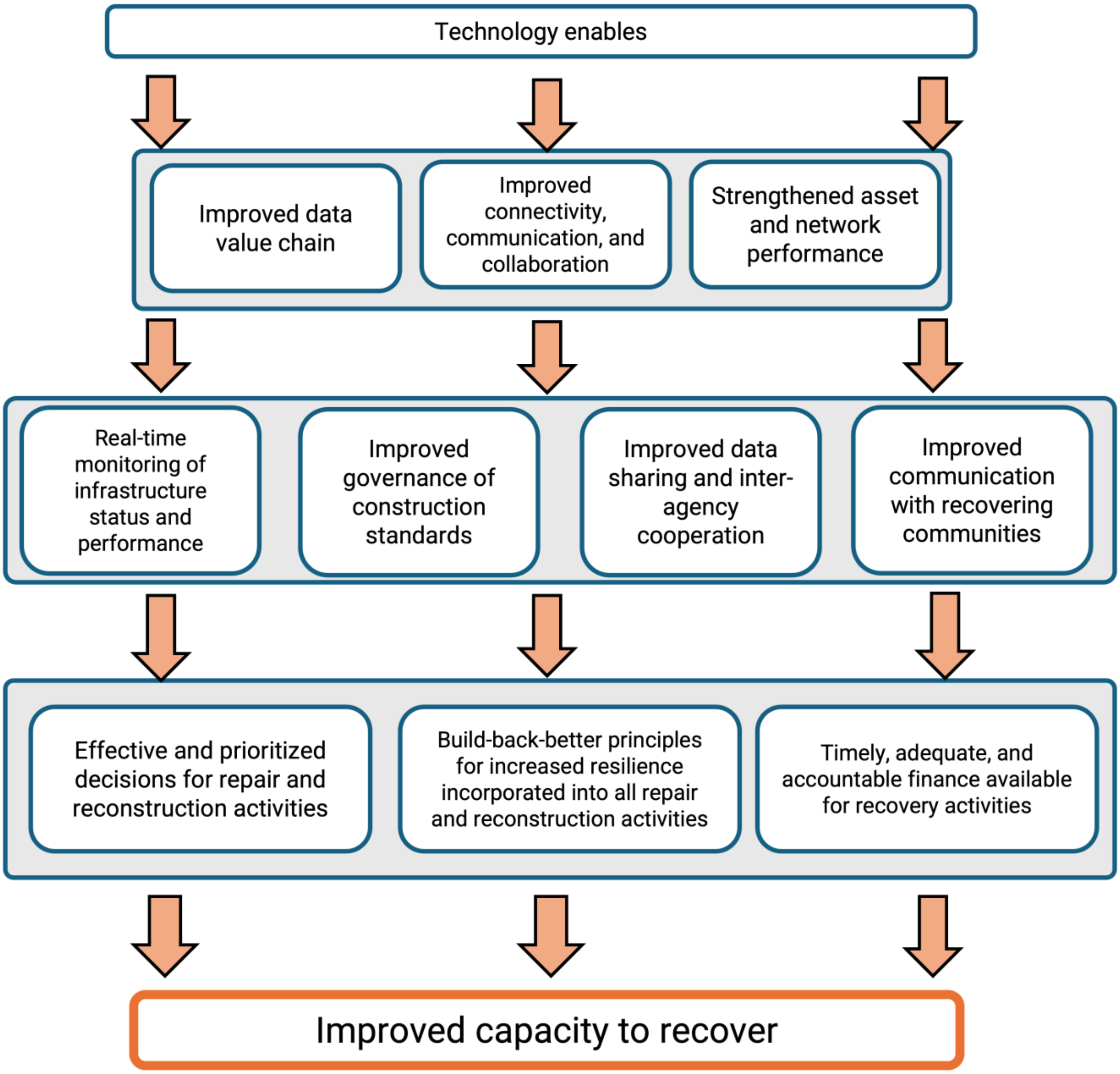

Figure 8: The pathways to resilience for technology in the capacity-to-recover phase

Source: Authors' analysis

4.6. Future Trends and Emerging Opportunities in Technology for Resilient Infrastructure

Similar to the past decade, the coming decade will bring significant changes to how we design, operate, and protect infrastructure systems. Rapidly evolving technologies offer new tools that can help governments, the private sector, and communities anticipate risks, respond to disruptions, and build infrastructure that is more adaptable and resilient in a changing world. Some of these technologies are already starting to reshape the landscape and are nearing readiness for wider adoption. Others are still on the horizon but hold exciting potential to radically improve resilience in the future. Monitoring these trends can help governments plan, invest wisely, and build institutional readiness for long-term transformation. This section highlights some of the current technological trends and directions that could support resilient infrastructure outcomes in the future.

Several technological trends have reached a point where they are now viable for large-scale implementation, particularly in low- and middle-income contexts. Chief among these is the growing availability of global open data and shared digital platforms. Open access to climate data, infrastructure asset information, and geospatial risk maps, which were not available earlier, helps governments in evidence-based decision-making. Although there are major challenges in adapting global analyses to inform local contexts at present. However, these platforms need to promote transparency and support interoperability to be most effective.

Many current innovations are driven by the rapid advances in digital technologies. Tools such as generative AI are beginning to assist in designing infrastructure layouts, running simulations of climate impacts, and optimizing maintenance schedules. ML continues to improve as the models are trained on increasingly larger real data sets. These AI systems will continue to benefit infrastructure stakeholders as computing capacity increases and becomes more efficient, and AI becomes faster and more accurate.

VR, once considered niche, is becoming a valuable tool for infrastructure planning and community engagement, enabling users to fully immerse themselves in future scenarios and collaboratively develop solutions. These capabilities are anticipated to expand and become more realistic, integrating seamlessly into real-life environments.

Expanding communication and connectivity is equally important. Internet access continues to improve in terms of both coverage and speed, with a major boost from recent advances in LEO satellite constellations. These systems offer affordable, high-speed internet even in remote regions, enabling data collection, real-time monitoring, early warning dissemination, and cloud-based coordination systems to function when terrestrial networks are down or unavailable.

On the hardware side, drones and remote imaging systems are already revolutionizing infrastructure monitoring and post-disaster assessment. When paired with AI-enabled software, they can detect cracks in bridges, determine prioritized maintenance or repair requirements, and assess the impacts of disasters within hours. Sensors and the broader IoT ecosystem are also developing and maturing, with associated rapid expansion in connectivity networks and data sources. Wearable devices are expected to continue to develop and may support resilience outcomes in new ways in the future.

In parallel, advances in battery technology are supporting more resilient energy systems. As battery longevity and charging times improve, the resilience of all infrastructure sectors that depend on energy will be enhanced.

Finally, the construction sector is undergoing a significant transformation. New materials such as carbon-sequestering concrete, self-healing polymers, and recycled composites are making infrastructure more durable, robust, and environmentally sustainable. Meanwhile, innovations in construction methods, such as large-scale 3D printing, are already being piloted to build structures at a fraction of traditional costs and timelines. These technologies are expected to continue to develop and improve capacities to respond to and recover from disasters in future years.

While the tools above are already being tested or deployed, the next wave of technologies is just over the horizon and could dramatically reshape resilience planning in the coming years. One of the most promising transformative technologies—although still in the early stages of development—is quantum computing. By offering exponentially faster problem-solving capabilities, quantum computers could support the resilience of infrastructure systems in numerous ways across the disaster and infrastructure life cycles.

New forms of digital collaboration are also emerging. As Web 3.0 technologies develop, we may see governments and communities co-design infrastructure in immersive, decentralized environments, also known as the metaverse. These tools could soon provide a space for testing policies, simulating investments, and training decision makers in complex infrastructure systems, all in a safe, virtual environment.

As satellite technologies become more sophisticated, their applications will expand further. Next-generation satellites are expected to offer higher-resolution imaging, higher-frequency data collection, and better communication and connectivity, which will benefit resilient infrastructure outcomes in many ways.

Cloud and edge computing, which enable data analysis and storage without the need for costly local servers, will continue to grow in capacity, driving increased opportunities for localized advanced analyses and collaboration.

The trajectory of innovation points towards a future in which resilient infrastructure is deeply digital, higher performing, and increasingly collaborative. However, strategic policymaking and effective decision-making are crucial to capitalize on the opportunities that technology will bring. Ministries and infrastructure agencies will need to invest in digital skills, regulatory reform, and innovation partnerships, particularly with academic and research institutions and private sector innovators.

4.7. Challenges and Limitations of Technology for Resilient Infrastructure

Technology is increasingly recognized as a vital tool for building resilient infrastructure, offering numerous pathways to enhance resilience across the disaster cycle. However, its adoption remains uneven and often fragmented. In LMICs, comprehensive integration across infrastructure assets and systems is especially rare, hindered by institutional, regulatory, financial, capacity, sustainability, suitability, and equity challenges. Understanding these barriers is essential to ensure that technologies deliver sustainable, inclusive, and resilient outcomes rather than creating new vulnerabilities.

Deloitte (2025) highlights the main barriers to the adoption of AI for resilient infrastructure (see Box 2). They mention high upfront costs, organizational resistance to change, issues with data quality, and weak regulatory environments, amongst others. Many of these barriers are similar to those faced by other types of technology as well. The key challenges and limitations in the use of technology for resilient infrastructure are discussed below.

BOX 2. Deloitte's *AI for Infrastructure Resilience* report

What are the main barriers to the adoption of AI?

Deloitte's report emphasizes that AI has the potential to significantly enhance infrastructure resilience by providing strategic tools across the entire disaster management cycle—planning, response, and recovery. The report lists some critical barriers to successful implementation:

- **Data quality and reliability:** The lack of large, varying, unbiased, accurate data sets to train AI effectively can lead to unreliable results and a lack of trust.
- **Integration with existing systems and processes:** There are challenges in integrating AI into legacy systems that were not designed to support modern AI technologies.
- **High upfront costs:** There are challenges in justifying the high initial costs for developing, testing, and implementing AI technology, as well as the costs of training, acquiring data, storage capacity, and upgraded computing power.
- **Uncertainty on returns on investment:** The technology is new and therefore does not have a track record of delivering returns on investments. The associated risks and uncertainty make it hard to make a strong financial case.
- **Weak regulatory environment:** Safe and ethical adoption of AI can be challenging when the regulatory environment is underdeveloped and not able to keep pace with technological advancements.
- **Lack of transparency:** Most AI systems are unable to clearly explain how they have reached decisions, causing challenges with transparency and auditability. This also makes it difficult to prove that regulations have been followed.
- **Organizational resistance to change and skills gaps:** The lack of a skilled and experienced workforce makes it difficult to effectively design, implement, and sustain AI systems. Additionally, resistance to change, risk, and innovation within organizations can pose barriers to the adoption of AI systems.

Source: Deloitte (2025).

4.7.1. Governance and Institutional Challenges

The lack of clear strategies and accountability is a major obstacle to the adoption of technology. Uncertainty exists about who is responsible for selecting, aligning, funding, managing, and sustaining technologies for resilient infrastructure. Fragmented mandates between ministries, combined with weak policy guidance, frequently result in siloed investments and duplicated efforts, undermining systemic resilience.

The mismatch between the rapid pace of technological advancement and the long design lives of infrastructure assets also complicates long-term planning. Institutional turf wars can further hinder collaboration, particularly when technical expertise and leadership on innovation are lacking. Procurement systems are typically inflexible and geared towards traditional products, excluding innovative solutions. Disconnects between stakeholders also limit systemic adoption.

Some countries have successfully overcome these challenges. For example, Singapore's GovTech and Smart Nation initiatives (see Box 5) demonstrate how a dedicated institution can integrate technology across sectors. However, in many contexts, institutional and cultural resistance to change persists. Overcoming these barriers requires establishing clear mandates, ensuring coordinated leadership, refining procurement processes, fostering supportive policy environments, and embedding innovation in standard operating procedures and regulations.

4.7.2. Financial and Economic Challenges

Financial constraints are among the most persistent barriers. Technologies typically demand significant upfront investments as well as ongoing expenses for maintenance, upgrades, and training. For many LMIC, especially Small Island Developing States (SIDS), limited fiscal space makes these costs prohibitive, particularly before benefits are demonstrated. Risk-averse environments and short-term fiscal cycles further discourage investment in untested innovations.

It is rare for countries to earmark funds for innovation, and traditional financing mechanisms often fail to incentivize adoption. However, not all technologies are prohibitively expensive. Many low-cost solutions, such as SMS-based early warning systems, solar-powered devices, and open-source mapping platforms, require relatively modest outlays, are easier to scale, and can deliver substantial resilience benefits in resource-constrained contexts.

Ultimately, sustaining funding and ensuring long-term operational viability remain major challenges. More investment in practical research and pilot projects would help evaluate technologies in new settings and bolster the financial case for resilience. Public–private partnerships (PPPs) have shown promise when structured to share benefits and risks, but these remain the exception (World Bank & PPIAF, 2022) (see Box 6).

4.7.3. Skills, Capacity, and Sustainability

The effectiveness of technology depends as much on people as on systems. Without ongoing training, tools may remain underutilized or be abandoned once donor projects or pilots end. Factors such as high staff turnover, weak local maintenance capacity, and limited strategies for digital skills development further undermine sustainability.

The rapid pace of innovation also creates constant demands for retraining and upgrading, which are difficult to meet without dedicated funding. Capacity building must therefore be treated as an ongoing process rather than a one-off training, ensuring that technologies are embedded within institutions and communities over the long term.

4.7.4. Data Gaps and Fragmentation

Reliable, accessible, and interoperable data underpins nearly all resilience technologies. However, in many cases, basic data on infrastructure assets is fragmented, outdated, or missing altogether. Information may be siloed across ministries, locked in proprietary formats, or prohibitively expensive when provided by the private sector.

Although global data sets are increasingly available, they often lack the granularity needed for cities, small islands, and rural areas. Weak digitization, inconsistent standards, and cybersecurity concerns compound these challenges. As a result, sophisticated tools such as AI, predictive analytics, or digital twins can generate misleading outputs because they are based on inaccurate and insufficient data.

Improving data governance, promoting open-data protocols, digitizing records, and building reliable, high-resolution local data sets are therefore essential for advancing digital resilience.

4.7.5. Cybersecurity and Privacy Risks

As infrastructure systems become increasingly digitalized, they are more exposed to cyberattacks, misuse, and data breaches. Critical services such as electricity grids and water utilities are attractive targets, and successful attacks can trigger cascading failures across multiple sectors.

At the same time, infrastructure systems collect increasing amounts of sensitive personal data. Without robust safeguards such as encryption, authentication, accountability measures, and legal frameworks, this information becomes vulnerable to misuse, eroding public trust in technological solutions. Building cyber-resilient infrastructure requires both technical and institutional measures, as well as a skilled workforce capable of anticipating evolving threats.

4.7.6. Equity Challenges

Technology adoption risks exacerbating existing inequalities as access to the internet, mobile networks, and digital literacy varies widely. In 2022, only 36 percent of the population in least-developed countries used the internet, compared with 66 percent globally. Disparities in mobile phone use and 5G coverage are similarly stark (ITU, 2023; 2024).

High-income countries are adopting advanced tools such as AI analytics, digital twins, and smart materials, while many low-income countries rely on simpler yet effective low-tech solutions. This divergence highlights the need to tailor technologies to the existing context. Without inclusive design and co-creation, technologies may replicate biases in data and decision-making, further excluding marginalized groups.

Appropriate low-cost technologies, such as text-based alerts, solar-powered systems, and open-source platforms, are essential in promoting equity. These solutions are often easier to deploy, maintain, and scale in resource-constrained areas, empowering community participation in the monitoring and maintenance of infrastructure.

4.7.7. Suitability Challenges

Not all technologies are contextually appropriate. Solutions developed for high-income, urbanized settings may be ill-suited to rural or low-resource environments. Relying on complex systems without adequate local capacity or maintenance infrastructure would lead to fragile, unsustainable outcomes.

Community-based alternatives, such as SMS-based early warnings, can often prove more reliable in resource-limited contexts. Logistical and connectivity challenges also highlight the need for locally appropriate solutions. For example, reliance on internet-based systems becomes a liability if terrestrial networks fail during disasters. Likewise, the majority of global supercomputing capacity required for AI is concentrated in high-income countries, restricting developing countries' ability to develop and apply AI solutions independently.

4.7.8. Environmental and Systemic Risks

While technologies can contribute to sustainability, through predictive maintenance, low-carbon materials, or optimized resource use, they can also generate environmental costs. For example, data centres and blockchain systems are highly energy-intensive, and rapid hardware turnover generates growing volumes of e-waste. In countries with limited recycling infrastructure, disposal of obsolete devices and batteries could contribute to health and environmental hazards.

Technological dependence can also create systemic fragility. Outages in power, internet, or vendor support may paralyse essential systems, especially during crises. To build resilience, it is essential to integrate redundancy, modularity, and fail-safe devices and also adopt circular economy approaches in procurement and system design.

4.7.9. Public–Private Challenges

The private sector is essential for developing and delivering resilience technologies, but incentives are often misaligned. Private operators may be hesitant to invest in projects that do not yield short-term profit or require data sharing. Public actors, meanwhile, may lack the tools for effective regulation or incentivizing collaboration.

Promising examples exist where contractual frameworks and shared-benefit models align interests. However, these remain limited. Building trust, creating regulatory clarity, and designing financing structures that reward resilience are essential to expanding such partnerships.

4.7.10. Connecting Technology to Decision-making

Finally, even when technologies generate valuable outputs, decision-makers may find it difficult to act on them if the outputs are not trusted, clear, and actionable. Bridging the gap between technical insights and policy decisions is therefore critical. Without this human connection, technologies risk producing knowledge that is unused or misunderstood, limiting their real-world impact.

4.8. Summary

In summary, technology is a powerful enabler of resilient infrastructure across the full disaster cycle, strengthening the capacity of systems and stakeholders to absorb shocks, respond effectively in emergencies, and recover sustainably. By optimizing the data value chain, fostering communication and collaboration, and strengthening the performance of physical assets and networks, technology can transform how infrastructure is designed, delivered, and maintained, and how it performs.

Technology adds value when it delivers context-appropriate solutions and is deployed wisely. Technologies will be more effective if they align with specific objectives and contexts, and are part of a broader strategic vision of disaster resilience. Infrastructure ministries, authorities, owners, operators, and other stakeholders must embed technology within broader systems of governance, financing, and institutional capacity.

Real-world case studies worldwide demonstrate that technologies are enhancing infrastructure resilience. Furthermore, tools are increasingly available as off-the-shelf, ready-to-use products and services, reducing the burden on resource-limited ministries and further increasing the opportunities for technology to be transformative.

Yet multifaceted challenges remain, including governance gaps, fragmented data systems, underdeveloped digital infrastructure, and low institutional capacity, which can all limit the impact of technological interventions. Addressing these requires not only technical fixes but also institutional reforms, inclusive approaches, and sustained investment in people and systems. By acknowledging and systematically addressing these barriers, governments and agencies can unlock the full potential of technology to strengthen resilience across assets, systems, and communities. Risks related to security, privacy, ethics, and inclusion must be proactively managed, and as new tools emerge, their limitations and unintended consequences must be continuously assessed.

The future is not just about smarter infrastructure; it is about infrastructure that is more adaptable, inclusive, and resilient, designed to handle the many risks in a complex and rapidly changing world.

5. From Innovative Possibility to Technological Reality

Technology holds immense promise for strengthening infrastructure resilience, as detailed in Section 4, provided the challenges are managed. However, there is often a considerable gap between ambitions and actual implementation. Turning the technology opportunity into tangible resilience dividends requires a strong enabling environment that supports the processes involved in introducing new technologies.

This section aims to equip public and private sector infrastructure stakeholders with the tools and guidance needed to bridge the gap in technology implementation. It first considers the key elements of a strong enabling environment that would provide the foundation required for the effective and successful adoption of technology for infrastructure resilience. Based on these elements, a readiness assessment checklist is introduced. Stakeholders can use this list to assess their current preparedness levels for the adoption of technologies and reflect on their strengths and weaknesses. The results of the assessment lead to the development of a practical roadmap for action to foster an enabling environment for the adoption and integration of technology.

5.1. An Enabling Environment for Successful Implementation of Technology for Resilient Infrastructure

The successful implementation of technology for resilient infrastructure requires an enabling environment that promotes, supports, and sustains the use of technology. Many countries have piloted promising technologies, only to see them fail to deliver lasting impact. Lessons from these pilots highlight that technology investments must be supported by a holistic enabling environment that addresses both the technical and non-technical factors required for success. The UNDRR report on technology for disaster risk reduction (UNDRR, 2025) emphasizes key elements (see Box 3) such as strong policy environments, reliability and trustworthiness of the technology, good governance and leadership, capacity building, and collaboration. Inter-American Development Bank’s (IADB) government digital transformation guide (Aitor et al., 2022) also discusses similar critical elements, as well as change management, inclusive and holistic approaches, and legal and regulatory environments (see Box 4).

BOX 3. Key Elements for Successful Implementation of Technology for Disaster Risk Reduction (DRR)

The United Nations Office for Disaster Risk Reduction (UNDRR) *Special Report on Technology for Disaster Risk Reduction* (Tech4DRR) (UNDRR, 2025) emphasizes several critical elements necessary for the effective use and adoption of technology in DRR:

- **Systems approach:** Adopting a holistic approach that considers interconnections between hazards, exposure, and vulnerabilities, recognizing that technologies must be context specific and tailored to local conditions and capacities.
- **Integration and scalability:** Evaluating and ensuring that technologies can be effectively integrated into existing systems and scaled appropriately across different infrastructure assets, systems, sectors, and socio-economic contexts.
- **Enabling policy environment:** Policies, standards, and regulatory frameworks that facilitate innovation, technology adoption, and sustainable implementation.
- **Reliability and trust:** Ensuring technology provides accurate, reliable, transparent, and timely data and analysis, crucial for building stakeholder confidence and for effective decision-making.
- **Inclusive and indigenous knowledge:** Ensuring technological solutions for DRR are culturally relevant, practical, and widely accepted by working with all groups in society, including vulnerable groups and indigenous communities.
- **Governance and leadership:** Strong strategic, institutional leadership and clear governance structures to support, coordinate, and sustain technological implementation efforts.
- **Capacity building:** Prioritizing training, education, and knowledge sharing to ensure stakeholders possess the necessary skills and understanding to effectively utilize technologies.
- **Interdisciplinary collaboration:** Encouraging cooperation across sectors, fostering partnerships between governments, academia, the private sector, and civil society to integrate diverse expertise into DRR initiatives.

By integrating these elements, technology adoption in DRR can significantly enhance preparedness, response, resilience, and sustainable recovery efforts.

Source: (UNDRR, 2025)

BOX 4. Focus: IADB's Government Digital Transformation Guide, a Guide to Progressing Digital Maturity in Government Systems

IADB's experience shows that technology alone is not enough. To ensure digital progress, institutions must establish the right foundations:

- **Governance and institutional framework:** A strong lead institution and clear governance mechanisms are necessary to coordinate efforts, avoid duplication, and guarantee alignment between sectoral strategies and national objectives.
- **Legal and regulatory framework:** Digital transformation requires legal certainty. Regulations must establish the foundation for digital identity, signatures, interoperability, and cybersecurity, ensuring that new processes remain valid and secure.
- **Digital talent and change management:** Skilled human resources are central to transformation. Employees must be trained and supported by structured change management to adopt new working methods.
- **Infrastructure and technological tools:** Core digital platforms and shared services (such as digital IDs, interoperability schemes, or cloud systems) must be developed once and reused, creating economies of scale and ensuring compatibility.
- **New digital processes and services:** Technology must be used to redesign and simplify processes, making them digital, efficient, and citizen-focused—avoiding the mistake of simply replicating paper-based procedures.
- **Holistic and inclusive approach:** Transformation must be comprehensive, involving all levels of government and society, with mechanisms in place to ensure participation, transparency, and accountability so that no group is left behind.

When these elements are in place, technology can enhance resilience by improving the efficiency, transparency, and continuity of infrastructure systems, even under conditions of stress or crisis.

Source: Aitor et al. (2022).

A strong enabling environment for the adoption of technology for resilient infrastructure will facilitate technology adoption and integration through policies, governance structures, and financing mechanisms based on strategic decisions that allow new technologies to be embedded in new and existing infrastructure systems. It will also ensure sustainability and scalability by enabling institutions to maintain, upgrade, and expand technology solutions without repeated external interventions. And finally, by ensuring sustainability, it will maximize the resilience dividend and contribute to improved service continuity, safety, and equity, while also providing broader social and economic co-benefits.

With a clear focus on technology for infrastructure resilience, this report identifies seven key elements of a robust enabling environment (see Figure 9):

i. Governance and strategic leadership

ii. Financial resources and sustainability

iii. Institutional capacity and human capital

iv. Data governance and digital infrastructure

v. Adaptive organizational culture and change management

vi. Monitoring, evaluation, learning, and evolving

vii. Ecosystem of partners and collaboration

Together, these elements provide a comprehensive foundation for ministries and private-sector infrastructure providers to move from isolated pilots to sustained, system-wide technological transformation. In the following sections, each element is described in detail.

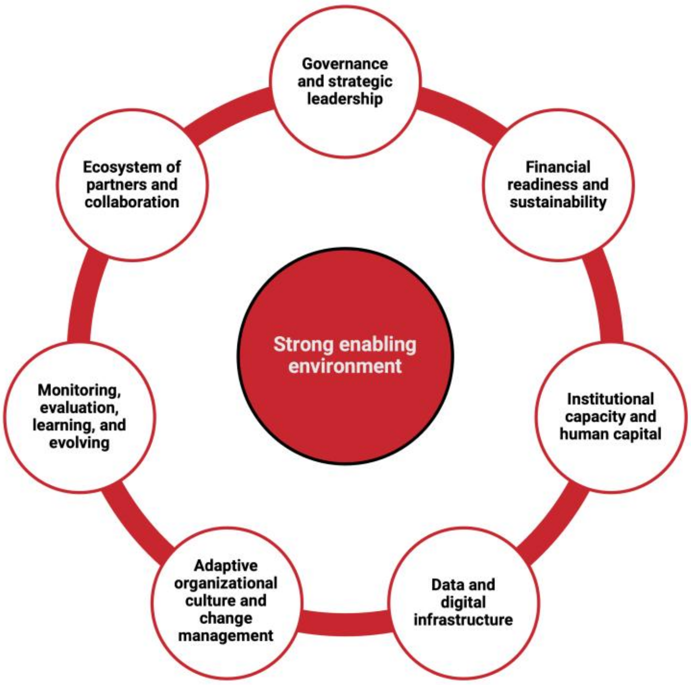

Figure 9: Elements of a strong enabling environment for technology adoption

Source: Authors' analysis

5.1.1. Governance and Strategic Leadership

Technical solutions alone are not enough to build resilient, technology-enabled infrastructure; robust structures, effective organizations, and decisive strategic leadership are necessary. Clear ownership of responsibilities, well-defined mandates, and accountability mechanisms form the foundation for aligning technology investments with strategic national resilience objectives.

Strategic leadership is especially important. Senior leaders must be able to mobilize resources, generate political support, and build coalitions that extend across ministries, regulators, and operators. Institutional leadership, in turn, must ensure that responsibilities are clearly defined, silos are eliminated, and decision-making processes are transparent and unified.

For policymakers, this translates to having a clear national vision or strategy for the role and use of technology in building resilience. Policies and regulations that provide certainty on issues such as data and technology use, resilience codes and standards, and threats such as cybersecurity should also be established. Additionally, it requires strong leadership and champions of technology or resilience, as well as effective mechanisms for coordinating technology-related issues. This can be achieved through a central umbrella unit, as in Singapore (see Box 5), or by clearly defining responsibilities and coordination mechanisms within ministries and agencies.

For infrastructure professionals, it requires sectoral-specific technology strategies that align with national policies and strategies, strong leadership driving technology and resilience solutions, and clear organizational structures and policies where innovation can thrive.

In practice, strong governance and leadership create the enabling environment where innovation can thrive in an aligned and coordinated way, ensuring that technologies do not remain isolated experiments but instead deliver lasting resilience benefits.

BOX 5. Singapore's GovTech Initiative

Singapore created the Central Government Technology Agency (GovTech) to lead digital transformation across all sectors, consolidating expertise, funding, and responsibility within a single authority. Unlike dispersed models where responsibility is split across ministries, GovTech develops and oversees strategy, sets standards, and drives innovation through multiple initiatives, including those around digitizing public services and advancing digital identities. The agency plays a central role in ensuring data interoperability, promoting cybersecurity, and fostering collaboration between the government, private sector, and research institutions. By embedding resilience into policy and practice, GovTech accelerates technology adoption across infrastructure systems and avoids duplication of efforts.

Source: Author's analysis

5.1.2. Financial Resources and Sustainability

Financial readiness is a determining factor for the adoption and long-term sustainability of technology in resilient infrastructure. While innovative solutions may be technically viable, their implementation requires financial mechanisms that can cover substantial upfront costs and provide ongoing funding for operation, maintenance, and upgrades.

At the policy level, this may involve establishing dedicated funding streams, incentives, or financing facilities with an appropriate risk appetite to encourage technological investments across infrastructure sectors (see Case Study 16). Governments may also need to create or pursue mechanisms to attract or leverage external resources, such as funding from donors and multilateral development banks, capital markets, or PPPs (World Bank & PPIAF, 2022) (see Box 6). Investment appraisal systems should incorporate cost–benefit analyses and business case requirements that explicitly account for resilience benefits, and these should be conveyed to implementing agencies. In addition, approval processes should mandate the inclusion of life cycle costing and long-term operation and maintenance plans to ensure impact sustainability.

Case Study 16: Catapult Network: Financial Innovation Hubs for Infrastructure Technology

One of the biggest challenges in infrastructure innovation is a lack of accessible funding to move promising ideas from the lab to the real world. In many cases, inventors and researchers struggle to find the resources, support, and partnerships needed to scale new technologies, especially in complex sectors such as energy, transport, and communications. The UK's Catapult Network was created to close this gap.

The Catapults are innovation centres that help bridge the valley between early-stage research and commercial success. They bring together government, industry, and academia to help ideas grow. To make this happen, each Catapult uses a balanced funding model combining public grants, collaborative R&D partnerships, and earned income from commercial services. This blend helps each Catapult stay focused on practical outcomes while reducing reliance on any single source of support. Each Catapult focuses on a particular sector, such as energy systems, digital infrastructure, or sustainable mobility, and offers targeted funding and technical support.

By lowering the financial and institutional barriers to innovation, the Catapults offer infrastructure innovators a better chance of success. They provide testbeds, funding pathways, and collaborative networks that help new technologies reach markets faster. Importantly, not only do they chase cutting-edge inventions, but they also help build systems that are more resilient, sustainable, and ready for the future.

Source: Catapult Network (2025)

At the infrastructure agency level, financial readiness could be demonstrated through the allocation of dedicated budget lines for technology adoption and the institutional capacity to manage funding from diverse external sources. Business cases or cost–benefit analyses developed for technology solutions within agencies should align with national priorities and financial appraisal standards. Medium- and long-term budgetary planning should explicitly include life cycle costs, covering operation, maintenance, and system upgrades to prevent technologies from becoming unsustainable after deployment.

Thus, financial readiness requires both enabling frameworks at the national level and practical budgeting and planning at the agency level. When these elements are aligned, they create the right environment for technology to move beyond pilot projects and deliver tangible, long-term resilience benefits.

BOX 6. PPP Contracts in an Age of Disruption: Adapting Long-term Partnerships to Technological Change

The World Bank report *PPP contracts in an age of disruption* (2022) highlights how disruptive technologies—such as renewable energy, artificial intelligence, blockchain, 3D printing, and autonomous vehicles—are reshaping infrastructure and creating new risks and opportunities for PPPs. Since PPPs are based on long-term contracts, often spanning 20 to 30 years, they must be designed and managed to cope with the rapid pace of technological and global disruption.

Opportunities: Emerging technologies can improve efficiency, prolong asset life, improve service quality, and lower costs. They also support new models such as digital procurement, blockchain-based smart contracts, and data-driven operations.

Risks: Long-term PPPs face a heightened risk of technological obsolescence, stranded assets, cybersecurity threats, and demand shifts resulting from decentralization or new mobility solutions. These risks can undermine revenue models, increase renegotiations, or create stranded investments.

Innovation resilience in project preparation: Future-proofing begins at project selection. Governments and investors must anticipate policy shifts (e.g., climate commitments), adopt flexible procurement models that reward innovation, and embed adaptive specifications in contracts. Shorter contract durations, gain-sharing mechanisms, and options for upgrades can balance innovation with bankability.

Managing existing PPPs: Flexibility is critical for ongoing contracts. Tools include adjustment clauses, insurance for cyber risks, well-defined force majeure provisions, renegotiation frameworks, and alternative dispute resolution. Strong relationships and governance mechanisms will be indispensable in reaching amicable solutions when technology shifts occur.

Broader lessons: Disruptive technologies differ from disruptive events (such as pandemics or financial crises), but both demand resilience. PPPs must be designed not only to deliver current service requirements but also to adapt to future shocks and opportunities.

The report concludes that governments should integrate flexibility, risk-sharing, and innovation incentives into PPP contracts, ensuring they remain bankable while being resilient to rapid technological change.

Source: World Bank and PPIAF (2022)

5.1.3. Institutional Capacity and Human Capital

Institutional capacity and skilled human resources are essential for embedding technology in resilient infrastructure. At the policy level, this may involve the establishment of a national technology skills strategy (see Box 7), including guiding frameworks for universities, colleges, and training providers to build digital capacity at scale. Such frameworks need to be accompanied by long-term funding commitments and measures to prevent the loss of skilled professionals to other markets or sectors. Governments may also create cross-sector forums or platforms that promote collaboration, peer learning, and shared capacity development across infrastructure sectors.

At the agency level, institutional capacity depends on whether organizations have enough staff with the technical expertise to design, procure, implement, and maintain technology solutions. Agencies may need to establish internal training programmes, supported by partnerships with universities, vendors, and research organizations, to ensure staff stay up to date with evolving technologies. Retention strategies are equally important: Agencies may need to create career pathways, incentives, or knowledge management systems to retain scarce digital and technical skills over time.

Institutional capacity also involves fostering a culture of continuous learning and professional development. Agencies may be expected to coordinate with other sectors, share lessons, and participate in joint initiatives to strengthen innovation ecosystems. Where capacity gaps are significant, partnerships with external organizations, through secondments, joint ventures, or knowledge exchanges, may help to accelerate skills transfer and reduce dependence on short-term consultants.

The combination of strong national strategies and robust institutional practices can build the human capital necessary to ensure that technology solutions are not just deployed, but embedded, maintained, and adapted for long-term resilience.

BOX 7. South Africa's Digital and Future Skills Strategy: Building Digital Capacity for Inclusive Development

South Africa's *National Digital and Future Skills Strategy* provides a national roadmap to equip citizens and institutions with the skills needed for the fourth industrial revolution. The strategy emphasizes that digital progress requires more than technical training; it demands systemic change across education, governance, and society. Its key elements include:

- **Foundational and advanced digital skills:** Coding, robotics, and digital literacy are introduced from primary school, while universities and technical colleges strengthen advanced training in fields such as data science, AI, and cybersecurity.
- **Workforce development:** Curricula and workplace training are aligned with the needs of digital industries, while new programmes support digital government roles and service delivery.
- **Bridging the digital divide:** Targeted initiatives expand connectivity and training for rural communities, women, youth not in education or employment, and persons with disabilities to ensure no group is left behind.
- **Awareness and citizenship:** Campaigns promote digital citizenship, cyber awareness, and the social value of digital skills, creating demand and participation across society.
- **Innovation and entrepreneurship:** Incubators, hubs, and entrepreneurship programmes help digital start-ups and innovators to thrive.
- **Research, monitoring, and governance:** A digital skills observatory, annual reporting, and dedicated coordination mechanisms ensure evidence-based decision-making and accountability.
- **Sustainable funding:** Establishing a digital development fund and leveraging existing national skills financing ensures long-term resources for implementation.

By integrating these actions, South Africa aims to create a digitally skilled population, foster innovation, and support more resilient and inclusive economic growth.

Source: Department of Communications & Digital Technologies (2020)

5.1.4. Data Governance and Digital Infrastructure

Reliable data governance and robust digital infrastructure are essential for embedding technology into resilient infrastructure systems. At the policy level, this means governments must establish clear national standards and regulatory frameworks for data collection, storage, interoperability, and cybersecurity. Ministries and coordinating bodies play a vital role in ensuring that data policies are harmonized across sectors, enabling secure data sharing and integrated digital platforms. Investments in core systems—such as broadband connectivity, cloud services, and cybersecurity infrastructure—are equally important to ensure that advanced applications like GIS mapping, IoT networks, and digital twins can operate effectively. Governments may also consider establishing shared service platforms or national data repositories to facilitate cross-sector collaboration, reduce duplication, and create economies of scale.

At the agency level, digital readiness depends on whether organizations can consistently collect and manage asset-level data, integrate new technologies into existing systems, and maintain secure and reliable information and communication technology (ICT) infrastructure. Agencies must be able to operate in accordance with national standards while developing internal systems tailored to their sector-specific needs—for example, asset management databases in transportation, smart metering in energy, or monitoring platforms in water utilities. Strong governance frameworks at the agency level should include clear data protocols, interoperability standards, and cybersecurity measures. Additionally, agencies might also need to enhance their connectivity, invest in modern ICT platforms, and ensure seamless integration of their digital systems with those of other public and private stakeholders.

National strategies and agency-level practices create the digital backbone for resilient infrastructure. When governments set enabling frameworks and invest in core infrastructure, and agencies develop secure, reliable, and interoperable systems, it results in an ecosystem in which technology can be scaled, adapted, and sustained over time to meet evolving risks and operational demands.

5.1.5. Adaptive Organizational Culture and Change Management

An adaptive organizational culture is essential for embedding technology into resilient infrastructure. At the government level, this involves establishing national strategies and leadership practices that demonstrate the importance of innovation, continuous learning, and transformation across all infrastructure sectors. Ministries and coordinating bodies may need to create cross-sector platforms where new technologies can be tested, the results shared, and successful approaches scaled. Strategic communication from senior leaders is vital for building legitimacy, reducing resistance, and encouraging collaboration between ministries, regulators, and agencies.

At the agency level, readiness depends on whether organizations actively foster a culture of innovation among staff. Agencies may need to implement internal processes that support piloting new solutions, gathering feedback, and adapting workflows to incorporate digital tools. Change management efforts should include staff training, structured engagement processes, and clear communication to reduce resistance and encourage buy-in at all levels. Recognition and scaling of successful technology initiatives can reinforce positive change and help embed new practices across the organization.

In summary, adaptive cultures at both the national and agency levels ensure that technology adoption goes beyond simple procurement. By embedding innovation, collaboration, and flexibility into everyday practices, organizations can remain responsive to evolving risks and capitalize on emerging technological opportunities.

5.1.6. Monitoring, Evaluation, Learning, and Evolving

Robust MEL systems are vital to ensure that technology for resilient infrastructure remains effective, scalable, and relevant. At the government level, ministries are tasked with establishing national MEL frameworks comprising appropriate indicators that measure not only operational performance but also contributions to resilience. They can also set up centralized systems to document and share lessons learnt across multiple infrastructure sectors, promoting systemic improvements and more strategic investment decisions. Participation in regional and global knowledge networks further enhances the ability to benchmark performance and learn from international experience.

At the agency level, MEL practices determine whether technology investments deliver value in day-to-day operations. Agencies must implement systems that track the performance of digital solutions, document lessons learnt from both successes and failures, and use this information to modify projects as they progress. Structured learning loops—including after-action reviews, internal knowledge-sharing sessions, or participation in sectoral communities of practice—help ensure that insights are institutionalized and not lost.

Together, robust MEL frameworks at national and agency levels create a culture of evidence-based decision-making. They ensure that technology initiatives are continuously adapted, improved, and scaled, enabling infrastructure systems to remain resilient to future shocks and evolving needs.

5.1.7. Ecosystem of Partners and Collaboration

Technology-enabled resilience is rarely achieved in isolation; it depends on a strong ecosystem of partnerships. At the government level, ministries play a central role in bringing together diverse actors—across the public and private sectors, academia, civil society, and international organizations—through a collaborative platform. Governments can foster enabling environments through supportive policies, incentives for PPPs, and mechanisms for inclusive engagement with communities and end users. By de-risking investments and guiding national research and innovation agendas, governments can accelerate the scaling of technologies while ensuring that benefits are equitably shared.

At the agency level, partnerships are often the primary means by which technology is designed, tested, and implemented. Agencies may need to collaborate with vendors, research institutions, and technology providers to customize solutions to sector-specific challenges. Engaging directly with users—such as commuters using transportation or households consuming water and energy—ensures that solutions are practical, inclusive, and aligned with community needs. Agencies that participate in professional networks or joint projects can also access valuable expertise and accelerate innovation cycles.

When governments and agencies cultivate strong collaborative ecosystems, they facilitate investments in knowledge, capital, and innovation needed for sustainable and impactful technology adoption. Such partnerships help minimize duplication, accelerate scaling, and ensure that resilient infrastructure initiatives are both technically sound and socially relevant.

5.2. Readiness Assessment Checklist: Diagnosing Implementation Capacity

The foundational elements for effective implementation of technology for resilient infrastructure are described above, and the level of maturity, capacity, and capability for each of these elements is unique to each stakeholder. Understanding these strengths and weaknesses is a critical first step toward building the enabling environment needed for successful, scalable, and sustainable technology use.

This section introduces a technology - readiness checklist, which provides a structured diagnostic and action-oriented framework for evaluating preparedness. This checklist allows infrastructure stakeholders to systematically assess their internal capacity to plan, implement, manage, and scale digital and technological solutions. Its purpose is to help ministries and private sector infrastructure operators identify and assess strengths and weaknesses in their current systems and to inform prioritized future actions to improve their technological readiness. The assessment also serves as a baseline for monitoring progress over time. It is designed to be flexible and capable of being adapted at the national, subnational, and organizational levels; impact-oriented and able to directly feed into programmes, investment strategies, and project design; and participatory through the use of facilitated interviews, document reviews, workshops, and cross-departmental consultations to gather data, information, and feedback.

The checklist can be used by infrastructure organizations of any size, regardless of their level of technological maturity or experience. It will, however, be most effective when used early in the planning process, prior to investments in technology. This would support a structured approach to adoption and implementation, ensuring that effective enabling conditions are in place and aligned.

The checklist is structured around the seven key elements introduced previously. For each of these elements, the checklist provides a set of four to six targeted diagnostic questions that help assess the organization’s current state of readiness to successfully adopt technology for resilient infrastructure. There are two sets of questions for organizations, depending on their responsibilities. The first set is aimed at stakeholders at the multisectoral or country/subnational level, who are responsible for fostering the enabling environment to implement technology for resilient infrastructure. The second set targets private- or public-sector organizations responsible for implementing technology to support the resilience of infrastructure services at the agency level. Although the two sets of questions are similar, the issues they focus on are different due to the distinct areas of responsibility.

The checklist is intended to be utilized either as part of a wider institutional assessment or review or on its own. It is intended as an internal self-assessment led by a small team within the organization, ideally through workshops or internal consultations, with cross-departmental input or with external facilitation or consultancy support, where independent facilitators guide the process to identify gaps and build consensus.

The checklist follows a four-stage process, starting with understanding the strengths and weaknesses, prioritizing areas of improvement, setting an action-based roadmap for improvement, and tracking progress.

5.2.1. Stage 1: Diagnose

The first stage establishes a baseline of technology-readiness. Using the diagnostic assessment, organizations evaluate their strengths and weaknesses across the seven key elements outlined in Table 1.

At the policy level, this may involve assessing whether national strategies, regulations, and financing mechanisms provide an enabling environment for digital transformation. At the agency level, the focus shifts to whether staff have the skills, budgets, and processes required to implement and sustain technologies.

The diagnostic process is structured around four to six targeted questions for each of the seven elements, with responses scored on a 0 to 3 scale and averaged to generate overall scores. Separate sets of questions are provided for overseers (e.g., national governments, regulators) and implementers (e.g., ministries, utilities, operators), reflecting their distinct roles in achieving technology-readiness. This scoring scale can be defined as follows:

- **0: Not in place:** No evidence of activity in this area; major gaps exist.
- **1: Emerging:** Early-stage efforts or partial actions exist, but they are not yet systematic or effective.
- **2: Developing:** Significant progress has been made, though with some gaps in coverage or consistency.
- **3: Established:** Fully developed, institutionalized, and functioning effectively.

Table 1 presents the diagnosis questions in the technology-readiness checklist.

Table 1: Technology-readiness checklist diagnosis questions

Group: Multisectoral country/subnational level responsible for developing the enabling environment to implement technology for resilient infrastructure	**Group: Infrastructure sector agency responsible for implementing technology to support increasing the resilience of infrastructure**
Governance and strategic leadership Goal: Effective governance ensures that the policy environment is strong, and strategic leadership ensures that technology initiatives are coordinated, supported by leadership, and aligned with national priorities.	
Is there a national vision or strategy for integrating technology into resilient infrastructure across all sectors?	Does the agency have a clear digital/technology strategy aligned with national visions, strategies, or policies?
Is there an effective central mechanism/agency/unit to coordinate technology and innovation initiatives for resilient infrastructure?	Is there clear leadership for technology/innovation initiatives within the agency with the right responsibilities and accountabilities to deliver this leadership?
Are roles and responsibilities for strategic leadership in innovation and technology adoption clearly defined across ministries, regulators, infrastructure agencies, and private-sector infrastructure owners and operators?	Are internal roles, responsibilities, and accountability for technology projects clearly assigned?
Do national policies, laws, and regulations enable and encourage digital and technological innovation in infrastructure, while safeguarding and protecting against the risks?	Are agency-level policies in place to guide procurement, operations, maintenance, security, and management of digital tools?
Do senior decision makers (e.g., ministers and permanent secretaries) actively champion technology-enabled resilient infrastructure?	Does leadership within the agency visibly support and champion technology adoption for resilience?
Financial readiness and sustainability Goal: Adequate financing ensures that technology can be implemented, maintained, and scaled.	

Are there national-level earmarked funding streams, incentives, or financing facilities, with appropriate risk appetites for technological and digital investment available to multiple infrastructure sectors for resilience?	Does the agency have dedicated budget lines for technology solutions for resilience?
Are external funding sources and arrangements (e.g., from donors, multilateral development banks, capital markets, and PPPs) available and able to be drawn to support technology investments for resilient infrastructure?	Does the agency have the ability and capacity to manage funding from external funding sources (e.g., from donors, multilateral development banks, and capital markets) or participate in PPPs?
Are business cases, cost–benefit analyses, and national investment appraisals required for technology investments for infrastructure?	Does the agency have adequate capacity to prepare business cases or cost–benefit analyses in alignment with national priorities for technology investments?
Are investment decisions required to include adequate financing plans for the sustainability of technology investments through the inclusion of operation and maintenance budgets and life cycle costing?	Are operation and maintenance and life cycle costs for technology investments factored into medium- and long-term budgets?
Institutional capacity and human capital Goal: Skilled personnel and strong institutions that are able to adopt, manage, and sustain technology solutions.	
Do decision makers have adequate technical expertise to guide agencies on technology adoption for resilience?	Does the agency have sufficient staff with digital/technical expertise to design, procure, operate, and maintain technology solutions?
Is there a national-level technology skills strategy (including educational frameworks to guide universities, colleges, schools, and training providers) to develop the scale and depth of human capacity in technological skills at all levels that responds to the national need to guide to retain skilled professionals in the workforce and avoid brain drain?	Are there internal processes to retain staff with scarce digital/technology skills?
Are there national/subnational educational programmes, with adequate funding attached, for training and capacity building in data, digital tools, and emerging technologies?	Are training and continuous professional development opportunities (including partnerships with vendors, universities, or research organizations) established and available for staff to keep pace with new technologies?
Are there established processes, partnerships, or adequate policies for national/subnational technological education frameworks to guide universities, colleges, schools, and training providers to develop the scale and depth of human capacity in technological skills at all levels that respond to the national need?	
Are there national/subnational mechanisms and fora to foster collaboration across infrastructure sectors to build shared capacity on technology and innovation?	Do you actively coordinate, share experiences and learning, or collaborate with other sectors to help foster technological innovation?
Data governance and digital infrastructure Goal: A strong digital and data foundation underpins all technology-driven resilience initiatives.	
Does the country have reliable basic digital infrastructure and connectivity services to support technology use across sectors?	Does the agency have reliable ICT systems and hardware, and adequate digital connectivity to operate technology solutions?
Are there national standards for data collection, interoperability, sharing (i.e., open data), and quality assurance that enable coordination and collaboration between agencies?	Is data on assets (status, performance, maintenance, etc.) collected systematically (even automatically) and stored in digital systems?
Are there open data initiatives to encourage and drive the sharing of key data related to resilient infrastructure across agencies and infrastructure sectors?	Are data-sharing frameworks or platforms being used to integrate and share data across different infrastructure sectors and between different agencies (e.g., meteorological agencies and geological agencies)?

Are there national policies, regulations, or laws for data privacy, security, and ethical use, and are they adequately monitored and enforced?	Are there clear protocols for data privacy, security, and ethical use within the agency?
Adaptive organizational culture and change management Goal: Institutions that embrace innovation and adapt and change to successfully adopt and sustain new technologies smoothly. *Questions are common across both groups*	
Does the agency have a culture at all levels that encourages innovation and technology adoption?	
Do staff feel able and encouraged to propose and test innovative digital solutions?	
Are there structured processes for piloting, evaluating, and scaling technology initiatives within the agency?	
Are staff and stakeholders engaged and consulted in technological transformation processes or pilots?	
Are there processes to address resistance, incentivize transformation, build buy-in, and adapt workflows for new technology initiatives?	
Are successful technology initiatives celebrated and scaled across departments?	
MEL and adaptation Goal: Continuous learning and evaluation ensure that technology investments are effective and inform improvements.	
Are national systems in place to monitor and track technological innovations for resilience across infrastructure sectors?	Does the agency monitor the performance and outcomes of its technology-enabled initiatives?
Are lessons learnt from technology initiatives systematically shared between ministries, agencies, sectors, and regions?	Are lessons from projects documented and shared internally and externally?
Does performance on initiatives inform national technology policy adjustments and future investments?	Are monitoring and evaluation results and learning used to adapt existing systems or design new initiatives?
Does the country participate in regional or global knowledge networks to benchmark progress and share learning?	Does the agency contribute to national or international learning platforms on technology for resilience?
Ecosystem of partners and collaboration Goal: Technology adoption thrives in a networked environment that leverages external expertise, resources, and partnerships with a range of stakeholders.	
Are PPPs promoted at the national level to support technology development and uptake?	Does the agency collaborate with technology providers, contractors, and research bodies to develop technological solutions or better deliver technology initiatives?
Are civil society and community groups engaged in shaping national technology policies and initiatives?	Are mechanisms in place to engage end users and affected communities in shaping technology solutions for resilient infrastructure?
Are platforms in place for inter-agency and public–private dialogue on technology for resilience?	Does the agency participate in communities of practice or working groups on technology adoption across different infrastructure sectors?
Are there national-level earmarked funding streams, incentives, or financing facilities to encourage technological innovation for resilient infrastructure in the private or research sector?	Does the agency have funding or budget for specific collaborations with the private sector or research organizations for the development of technological solutions for building resilience?

Source: Authors' analysis

Each question is scored, and these are averaged for each of the seven elements to give an overall score for that element. The questions are designed to be specific enough to prompt reflection and discussion yet general enough to allow adaptation to local contexts and different stakeholders and infrastructure sectors.

5.2.2. Stage 2: Prioritize

Once the diagnostic baseline is established, results are synthesized to identify the areas where intervention will be most effective. Visualization tools, such as radar charts or traffic-light ratings, help in making the findings clear and actionable. The blue shading in Figure 10 gives an indicative example of how the diagnosis might appear on a radar chart. A balanced, outward-reaching radar shape implies overall strength across all elements, whereas a skewed profile reveals areas where readiness is weak and targeted action is required.

The analysis will identify different performance readiness levels, based on the scores, which can be tailored for the particular situation:

- High-performing domains (e.g., score >2.2): To be leveraged or scaled.
- Moderate domains (e.g., score >1 and <2.2): Need incremental improvement or targeted support.
- Low-performing domains (e.g., score <1): Require foundational investment or urgent reform.

For example, an organization may demonstrate strong adaptive culture and change management but show significant weaknesses in data governance, institutional capacity, or financing mechanisms. These gaps then become the clear priorities for roadmap development.

The prioritization process transforms raw diagnostic results into a practical set of focus areas for investment and reform. It ensures that limited resources are allocated to the most critical needs, while also highlighting where existing strengths can be developed further.

5.2.3. Stage 3: Act

The third stage translates the identified priority gaps into clear, structured actions. This is where diagnosis and prioritization evolve into a practical roadmap for implementation.

Using the results of the technology-readiness assessment checklist, a roadmap should be developed to target specific improvements that are needed to increase readiness to adopt technology for resilient infrastructure. A roadmap will offer a structured approach to move from priorities to action. A robust roadmap bridges the gap between recognizing challenges and delivering reforms by setting clear objectives, responsibilities, timelines, and resources. Effective roadmaps:

- combine quick wins (e.g., establishing data-sharing protocols and launching staff training pilots) with longer-term systemic reforms (e.g., revising national procurement policies or creating new financing facilities);
- organize actions based on the seven elements of readiness, ensuring a comprehensive and balanced approach; and
- indicate for each action, along with the objective, the actor responsible; coordination needed and other dependencies; resource requirements; timelines; and measurable performance indicators. The actions must be politically and financially feasible within current and future constraints.

At the policy level, actions may include establishing national strategies that define technology's role in strengthening resilience or updating data security policies. Governments could also create incentive schemes for digital investment or conduct nationwide training programmes.

At the agency level, actions often focus on internal operations and are directed towards the day-to-day management of infrastructure systems: improving budget planning for life cycle costs, upgrading data infrastructure, creating digital transformation units, strengthening staff development, or forging partnerships with universities, private innovators, or peer agencies.

The process of drafting the roadmap is as important as the document itself. Stakeholders across ministries, agencies, operators, and users should be engaged in workshops and consultations to agree on priorities and responsibilities. This builds ownership and collaboration, reducing the risk of plans stalling due to a lack of buy-in.

5.2.4. Stage 4: Track

The final stage establishes mechanisms for MEL. Repeat assessments—conducted annually or biennially—allow institutions to measure progress, assess the impact of interventions, and identify persistent gaps. The red-shaded region in Figure 10 gives a visual indication of what the progress may look like in a subsequent assessment after application of a robust roadmap (the initial diagnosis results are in blue).

Tracking occurs at multiple levels:

- At the policy level, results can support national reporting on resilience, climate adaptation, or sustainable development goals.
- At the agency level, it strengthens accountability in investment planning, staff performance, and budget allocation.

Importantly, tracking is not only about measuring outputs but also about institutional learning. By embedding feedback loops, organizations can ensure that evidence shapes future reforms, capacity-building efforts, and investment decisions. This transforms the checklist into a living tool that supports continuous adaptation and resilience.

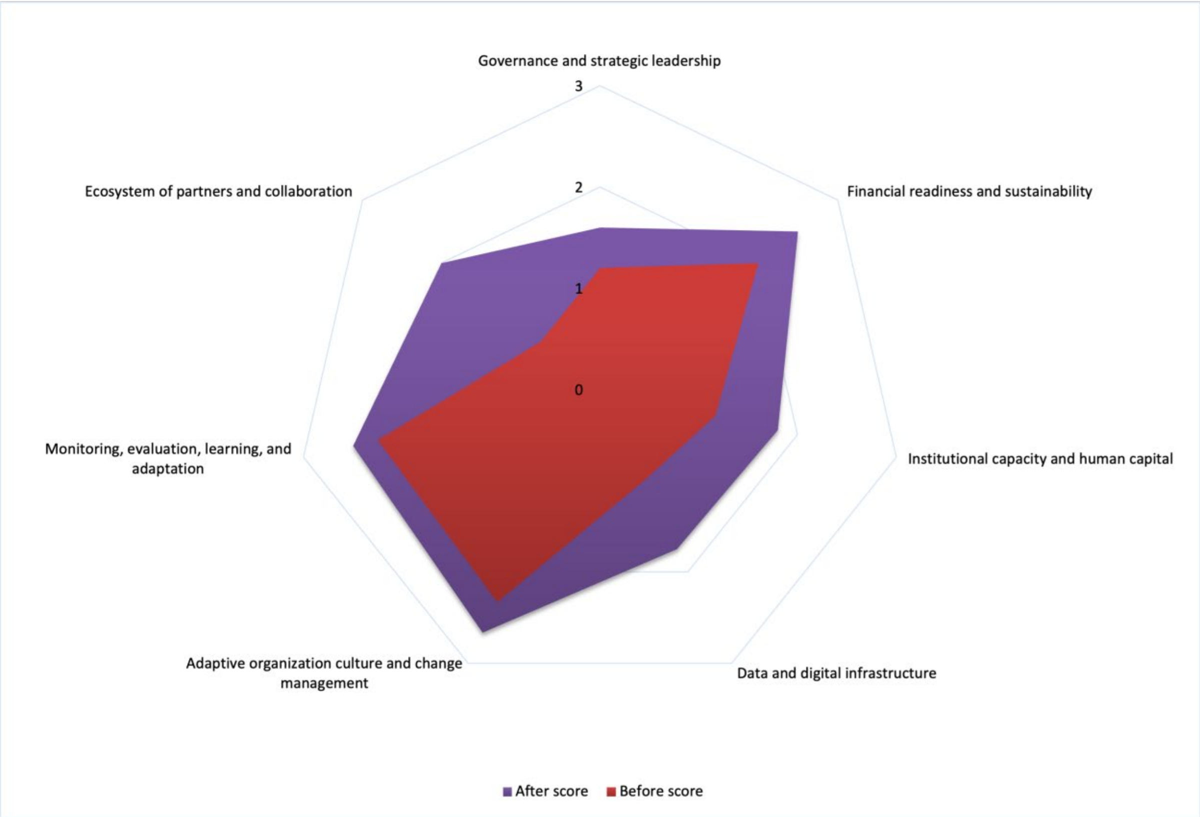

Figure 10: An illustrative example of a radar chart for the CDRI technology-readiness checklist

Source: Authors' analysis

5.3. Conclusion: Building a Culture of Responsible Tech Adoption

Resilient infrastructure depends not only on the adoption of technologies but also on the systems, institutions, finance, and people involved in the implementation and maintenance of such infrastructure. This section introduced seven key elements that support a stakeholder's readiness to implement technology. Building on these seven themes, a technology-readiness checklist was presented that can help stakeholders diagnose institutional strengths and gaps and build a roadmap for improvement.

Crucially, investing in institutional readiness today unlocks tomorrow's resilience dividend. By strengthening the foundations for technology implementation, governments can future-proof infrastructure, improve service delivery, and better protect populations from shocks and stresses. These tools are not a goal in themselves, but they provide a practical, proven way to achieve those goals.

6. Conclusion

This background report demonstrates that technologies—such as digital platforms, innovative construction techniques, and low-cost community tools—have the potential to enhance infrastructure resilience. By increasing risk awareness, strengthening coordination, ensuring service continuity, and accelerating recovery, these technologies can help societies capture the resilience dividend. This would translate to reduced losses and disruptions and help communities reap the social and economic benefits of investing in resilient systems.

Yet technology is not a silver bullet. Persistent challenges, including governance gaps, financing constraints, limited skills, weak data systems, risks of exclusion, and environmental costs, must be addressed to ensure that technologies deliver their intended benefits. The report emphasizes the importance of building robust enabling environments where governance, financing, institutional capacity, and inclusive approaches work together to support sustainable technology adoption.

Moving forward, governments and infrastructure agencies must:

- diagnose their readiness for technology adoption using structured tools;
- prioritize areas where action will deliver the greatest impact;
- act by developing sequenced, accountable roadmaps that integrate both quick wins and long-term reforms; and
- track progress over time, embedding learning and adaptation into future investments.

This four-stage readiness process provides a practical pathway for countries to systematically harness technology for resilience rather than adopting solutions in an ad hoc manner. It ensures that resilience dividends can be captured consistently across assets, systems, and users.

The findings of this working paper are incorporated in the GIR 2025 report, where they will be integrated with insights from the other work streams on finance, institutions, governance, and nature-based solutions. Together, these contributions will help countries and stakeholders in moving from conceptualization to actual implementation, ensuring that investments in infrastructure resilience are technically sound, financially viable, institutionally feasible, and socially inclusive.

In conclusion, technology offers unprecedented opportunities to strengthen the resilience of global infrastructure systems. By making deliberate, evidence-based, and inclusive choices now, countries can ensure that technology becomes a driver of sustainable development and a cornerstone of future-ready infrastructure.

[1] The dollar sign indicates US dollars throughout this chapter.

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